The Container Tree Nursery Manual

Volume Six
Seedling Propagation

Chapter 2
Seed Propagation

6.2.1 Introduction

By far, the majority of forest and conservation species are propagated from seed. On a number-of-seedlings basis, 95% would be a conservative estimate due to the preponderance of commercial forest trees grown from seed. On a number-of-species basis, however, the percentage would be somewhat lower because many native species can only be produced vegetatively.

There are both biological and economic reasons for the popularity of seed propagation. First, and most importantly, it preserves the wide genetic adaptation which is critical to successful seedling establishment and growth in the natural environment. Most natural resource outplantings have the objective of preserving the natural variation of a plant species, making propagation from seed the logical choice. In addition, seed propagation is almost always the least expensive propagation method; typical seed costs for forest and conservation species ranged from less than 25 cents to 35 dollars for a thousand seeds in 1995 (table 6.2.1). Seeds also are easy to ship and are not restricted by the phytosanitary restrictions of vegetative propagation material (Macdonald 1986). Finally, seed propagation is advantageous because seeds of most species can be stored for several years.

The primary objective of seed propagation is to promote rapid and complete germination and establishment in the growth container. To achieve this successfully and consistently, growers must have a basic understanding of seed biology.

6.2.1.1 Basic seed biology

Novice nursery managers must understand some basic biology of how fruits and seeds develop to be certain that seeds that they collect or buy are of high quality. First, some definitions (Bonner and others 1994):

Fruit = A ripened ovary that develops and surrounds the seed after fertilization. Although this term is most commonly associated with angiosperms, the word fruit can refer to any seed-bearing structure, including cones.

Seed = A ripened ovule consisting of an embryo, its stored food supply, and protective coverings.

Plants grown in forest and conservation nurseries have many different types of fruits and seeds (figures 6.2.16.2.6), and nursery managers must be familiar with characteristics of both. When asked to propagate an unfamiliar plant, inexperienced growers should consult one of the basic references listed in section 6.2.11. In particular, *Seeds of Woody Plants in the United States* (Schopmeyer 1974; Bonner in press), the *Tree Seed Technology Training Course Manuals* (Bonner and others 1994), *A* Guide *to the Biology and Use of Forest Tree Seeds* (Leadem 1996), and *Anatomy and Morphology of Conifer Tree Seed* (Kolotelo 1997) provide excellent coverage of the basic principles of seed biology.

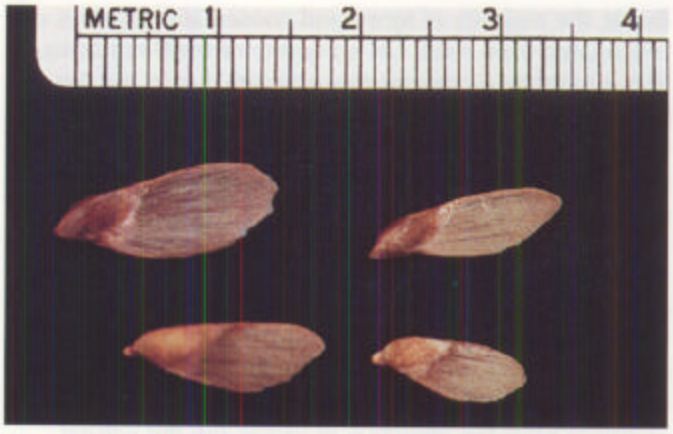
Nature has designed fruits and seeds to assure the wide dissemination and successful establishment of seedlings, but many of these ecologically useful adaptations are actually a hindrance to easy seed propagation. In fact, for propagation purposes, fruits have no use and some

Table 6.2.1—*Seed costs for the forest and conservation species shown in figures 6.2.1 to 6.2.6 are relatively inexpensive but vary considerably due to the difficulty of collection, processing, and seed weight*

Species	Cost ($)		No. of seeds		Cost ($) /1,000 seeds
	per kg	per lb	per kg	per lb	
Rocky Mtn. Douglas-fir	66	30	70,500	32,000	0.94
Coastal Douglas-fir	132	60	88,200	40,000	1.50
American plum	22	10	1,920	8,701	11.48
Shagbark hickory	7	3.50	220	100	35.00
Vinebark maple	33	15	10,190	4,620	3.25
Quaking aspen*	1,433	650	7,938,000	3,600,000	0.18
Antelope bitterbrush	55	25	34,000	15,400	1.62

Source: 1995 costs from Lawyer Nursery; seed data from Schopmeyer (1974).
* Only by special collection.

A



B

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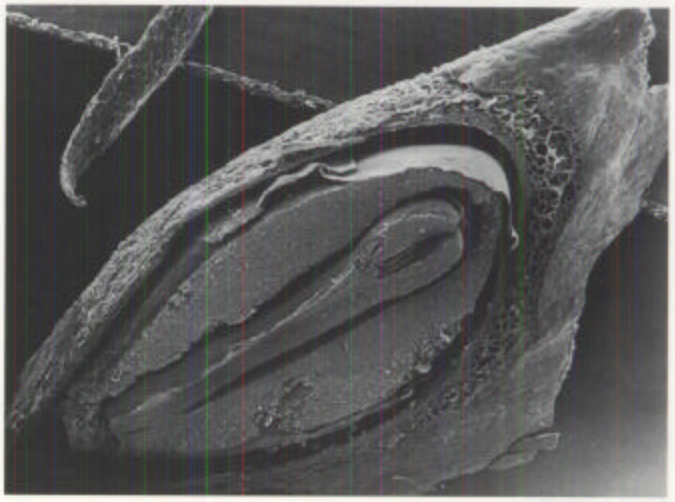

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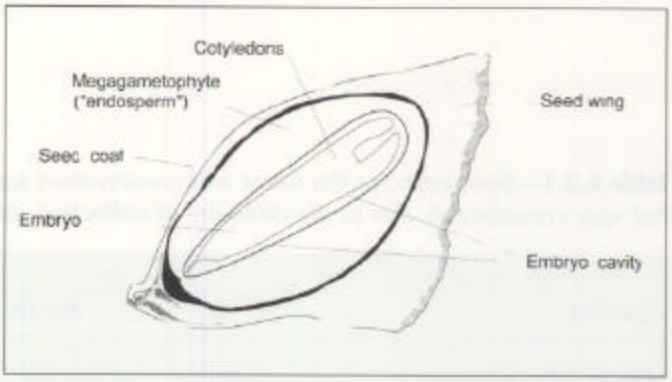


Figure 6.2.1—*Examples of typical fruits and seeds of forest and conservation plants (Douglas-fir):* **A** *= cone,* **B**= *seed,* **C** *and* **D** *= seed cross-section (C, courtesy of L.E. Manning, Canadian Forest Service).*

2A

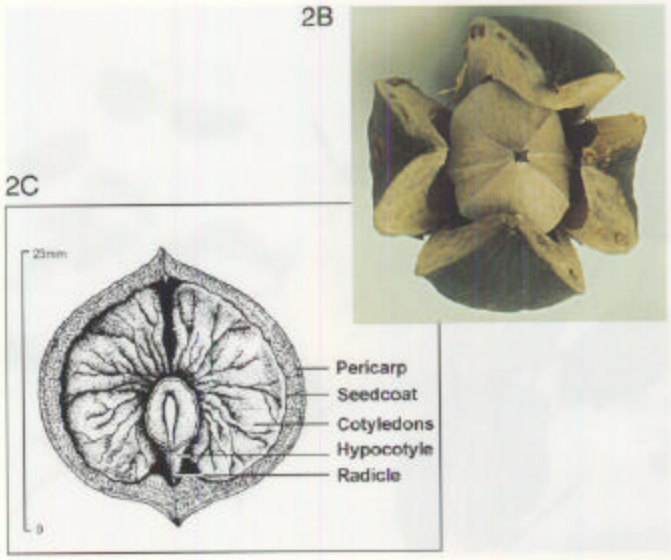
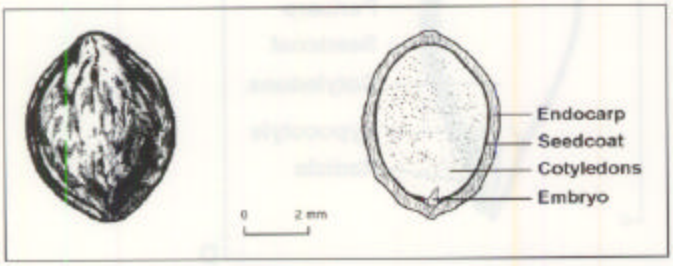


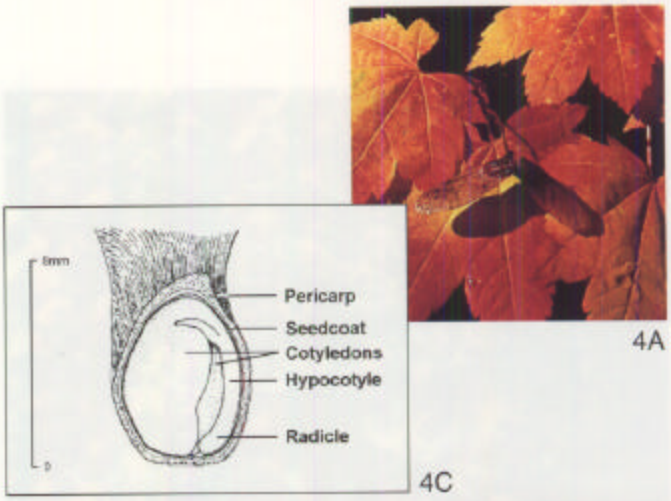
Figure 6.2.2—*Examples of typical fruits and seeds of forest and conservation plants (shagbark hickory):* **A** *= fruit,* **B** *= seed in husk,* **C** *= seed cross-section (A&B, courtesy of Jim Rathert, Missouri Department of Conservation; C, modified from Bonner and Maisenhelder 1974).*

3A



3B

Figure 6.2.3—*Examples of typical fruits and seeds of forest and conservation plants (American plum):* **A** *= fruit;* **B** *= seed, and seed cross-section (A, courtesy of Randy Moench, Colorado State Forest Service; B, from USDA 1948).*



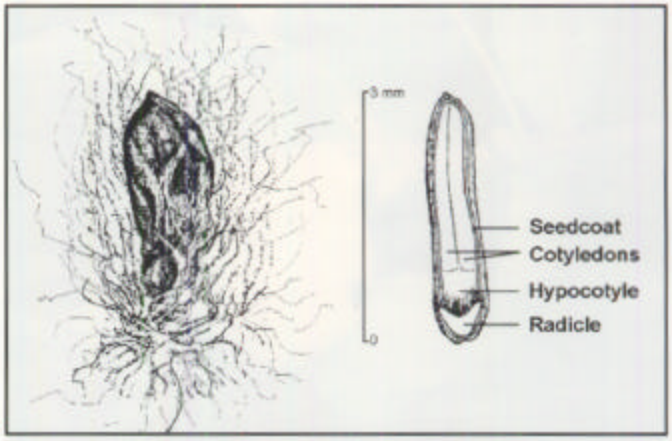
4A

4C

4B

Figure 6.2.4—*Examples of typical fruits and seeds of forest and conservation plants (vine maple):* **A** *= fruit,* **B** *= seed,* **C** *= seed cross-section (C, from Olson and Gabriel 1974).*

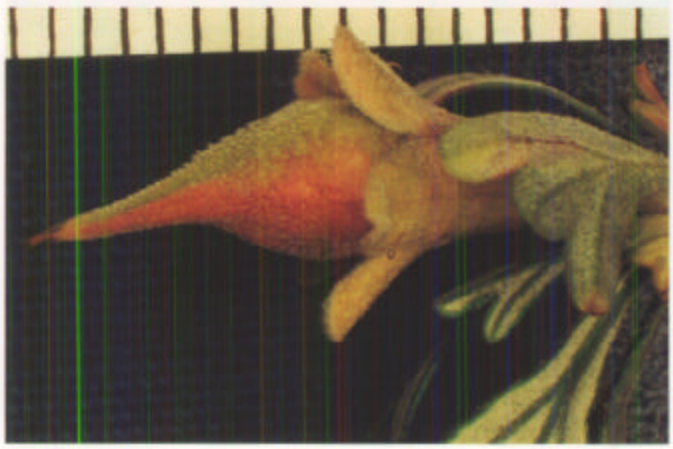
A



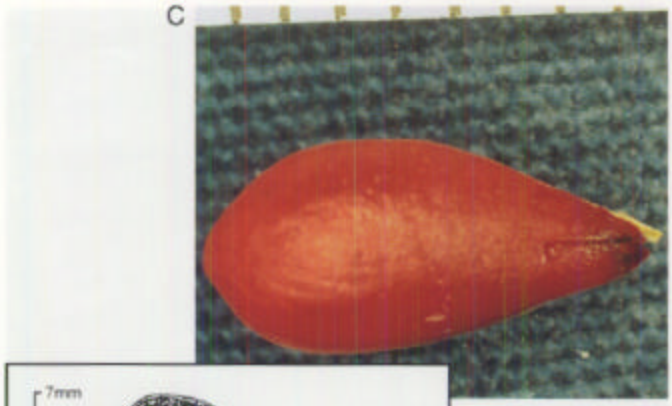
B

Figure 6.2.5—*Examples of typical fruits and seeds of forest and conservation plants (quaking aspen):* **A** *= fruit,* **B** *= seed, and seed cross-section (B, from USDA 1948).*

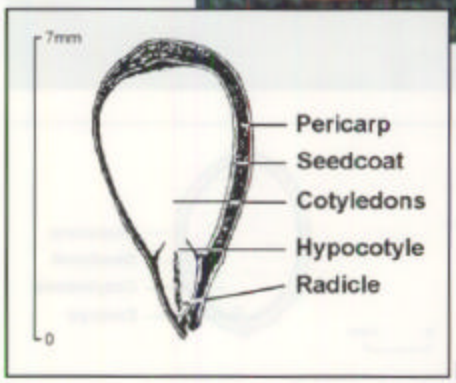
A



B



C



D

Figure 6.2.6—*Examples of typical fruits and seeds of forest and conservation plants (antelope bitterbrush):* **A, B** *= fruit,* **C** *= seed,* **D** *= seed cross-section (B & C, courtesy of Nancy Shaw, USDA Forest Service; D, from Deitschman and others 1974).*

actually serve the ecologically useful, but horticulturally frustrating, function of delaying seed germination (table 6.2.2). For example, chamisso sedge apparently has a chemical germination inhibitor in the papery hulls surrounding the seed, and germination of some seedlots has increased 70% by simply removing the hull (Trindle 1995).

Nursery managers collecting their own seeds will have to separate the viable seeds from their fruits and clean them. Before buying from a seed dealer or accepting seeds from a potential customer, managers should make a careful inspection to make certain that they have been properly identified and cleaned. For conifers this inspection is relatively easy but becomes more critical when dealing with seeds of other forest and conservation plants that are less commonly cultivated. It would be very frustrating to discover right before sowing that a new customer has collected the wrong part of the flower or that the fruits still need to be processed. For example, a nursery that was asked to grow some alder plants from seeds supplied by the customer discovered that male catkins had been collected instead of female cones!

Typical fruits of forest and conservation plants are of three general classes, and each requires different collection and processing procedures (Krugman and others 1974):

1. Multiple-seeded dry fruits ("cones") that release their seeds at maturity, for example, Douglas-fir (figure 6.2.1 A).
2. Single-seeded dry fruits that separate from the parent plant at maturity, for example, *Carya* spp. (figure 6.2.2A).
3. Fleshy fruits that separate from the parent plant at maturity with their seeds enclosed, for example, *Prunus* spp. (figure 6.2.3A).

Seeds of different plant species vary considerably in size, appearance, and internal anatomy, but each consists of three basic parts: embryo, food storage tissues, and seedcoat. The embryo is the miniature new plant that will eventually develop into the seedling. The seeds of some species have undeveloped embryos, whereas seeds of other species, such as Douglas-fir, have embryos that look like miniature seedlings with seed leaves (**cotyledons**), and an undifferentiated stem-root axis consisting of the **hypocotyl** and the **radicle** (figure 6.2.1 C). Food storage tissues provide a source of nutrition for seed germination and seedling establishment. The seed coat provides mechanical protection for the embryo and prevents desiccation.

Growers must become familiar with the seed anatomy of plants that they wish to propagate for several reasons:

1. They must be able to determine if seeds are mature and viable when they collect fruits or buy cleaned seeds.
2. The type of seed coat and condition of the embryo may indicate whether presowing treatment is needed.
3. The seed structure gives a hint about what type of care will be required after germination.

For example, a mature Douglas-fir seed has an embryo which is at least three-quarters of the length of the seed cavity and is surrounded by a firm white megagametophyte ("endosperm") (figure 6.2.1 C). Seeds with a shorter embryo or with a megagametophyte that is soft and milky were collected when cones were immature. By contrast, a mature seed of Prunus spp. (figure 6.2.3B) has a tiny embryo with huge cotyledons, no endosperm at all, and a thick seed coat that requires mechanical or chemical pretreatment before sowing. Aspen seed has no

Table 6.2.2—*The presence of the fruit of southern magnolia reduces both the percentage and the rate of seed germination*

Seed condition	Seed treatment	Percent germination	Germination rate (days)
Seed with fruit	None	29	125
Seed with fruit	24-hour water soak	21	125
Seed without fruit	None	73	125
Seed without fruit	24-hour water soak	76	125
Seed without fruit	3-month cold-moist stratification	~100	35

Source: Modified from Dirr and Heuser (1987).

substantial food storage organs and a thin seedcoat (figure 6.2.513), which means the resultant germinant will be relatively weak and require careful culture. A good discussion about the anatomy and morphology of commercial conifer seeds can be found in Kolotelo (1997), which also includes excellent color illustrations.

The genetics of a typical conifer seed contains a mixture of three distinct genomes. The embryo contains a mixture of male and female genes, but the megagametophyte and the seed coat are both strictly female. This has operational significance because the seed coat can be the cause of seed dormancy if it inhibits the penetration of water and oxygen and thereby delays germination. The female-derived megagametophyte also has a strong influence on seed germination and seedling establishment (El Kassaby and others 1993a).

6.2.1.2 Importance of seed source

The concepts of **seed source** or **provenance** are of paramount importance when propagating forest and conservation plant species from seeds, and refer to the geographical area (seed zone) in which the seed was collected. Seed zones for some species are quite large, whereas those for other species can be very small. In mountainous areas, the seed source must also be identified by elevational zones that can be as narrow as 152 m (500 ft) (see figure 1.1 AA in volume one of this series).

Seed source affects seedling performance in 2 ways: growth rate and cold tolerance. In general, seedlings grown from seeds collected from higher latitudes or elevations will grow slower but tend to be more cold hardy during the winter than those grown from seeds from lower elevations or more southern latitudes. For example, white ash seedlings grown from seed collected from northern Michigan became cold hardy earlier in the year and hardened to an average of -38 °C (-36 °F), compared to seed collected from southern Mississippi which hardened much slower and only reached a maximum hardiness of -27 °C (-16 °F) (Alexander and others 1984). **So, unless research has shown otherwise, seed should always be collected from the same seed zone in which the seedlings are to be outplanted.**

Research on genetic adaptability may prove that one seed source is superior for a particular geographic region. For example, the Niobrara River, NE, source of ponderosa pine was tested at locations all over the Great Plains and was found to exhibit significantly better survival, growth, and resistance to pine shoot moth (Read 1983). Likewise, genetic research has shown that loblolly pine seeds from the Livingston Parish region of Louisiana grow faster and have more disease resistance when planted all over the South (Wells and Wakeley 1966). More intensive research can identify specific "plus" or "elite" trees that have proven genetic superiority and eventually develop seed orchards from repeated selection and field testing. For most forest and conservation species, however, the degree and range of adaptation is unknown, so seedlings should always be outplanted back into their seed zone of origin. Rudolf (1974) has brought together the available information on recommended seed collection zones for a number of important northern and western coniferous species. Government forestry agencies also have published seed transfer guidelines (see section 1.1.1 .1 for more discussion on the importance of seed zones in nursery culture).

6.2.1.3 Genetically improved seeds

Customers may specify that their seedlings be grown from seeds specially selected for fast growth rate, disease resistance or other genetically controlled factors. This special seed can be considerably more expensive so single-seed sowing may be requested. The basics of producing genetically improved seed and managing seed orchards is explained in detail in Rudolf and others (1974).

6.2.2 Obtaining High-Quality Seeds

The key to producing seedlings of consistently high quality is prompt and uniform seed germination and vigorous early seedling growth, and therefore the importance of insisting on quality seeds cannot be overemphasized. **Even the best nursery practices cannot overcome the cultural problems that result from poor seed quality.** In fact, the development of container nurseries has highlighted the importance of seed quality. In standard bareroot seedbeds, seed germination is hidden from view so the high number of seeds that are lost to pathogenic organisms or weather problems is not evident. By contrast, seeds sown in sterile growing media in containers and germinated under ideal conditions can be easily observed, thus making poor seed quality much more apparent (figure 6.2.7). Nursery managers who sow cheap seeds of unknown quality will pay for their false economy. Seed costs are only about 1 % of total seedling production. Thus, the cost of purchasing high-quality seeds can easily be justified when compared to the costs of maintaining a seedlot with many empty cells and weak seedlings for the remainder of the growing season. (Sample production costs are given in the Nursery Management chapter in volume one of this series.)

The term **seedlot** should be discussed at this point. A seedlot is usually defined as a quantity of seeds from the same species that was collected from a specific seed zone or source and that is of reasonably uniform quality. The term seedlot carries through into nursery culture, where it signifies the batch of seedlings grown from that particular batch of seeds.

Figure 6.2.7—*Poor-quality seed can be a disaster in a container nursery because valuable bench space is wasted for the entire growing season.*

6.2.2.1 Collecting and processing seeds

Some forest and conservation nursery managers prefer to collect and process their own seeds because then they have complete control of seed source and seed quality. It can also be more economical to collect and process seeds if collection coincides with times when the nursery crew needs additional work. For some conservation species with wide areas of adaptation, seed production areas (figure 6.2.8A) can be established right in the nursery and, in some cases, windbreaks can be planted with species of the desired seed source. Other nurseries have access to seed orchards (figure 6.2.813). For most species, however, seeds must be collected near the outplanting site.

A

B

Figure 6.2.8—*Seeds of forest and conservation species can be purchased from commercial dealers or custom collected. Some nurseries establish seed production areas* (**A**) *or have access to seed orchards* (**B**).

Seed collection and processing requires technical knowledge and specialized equipment, not to mention a considerable time commitment. Many forest and conservation species do not produce seeds every year, and crops of species growing in the same plant community do not necessarily produce crops in the same year (figure 6.2.9). Even if they do, crops can be widely scattered and may not occur in the desired seed zone. Seed quality also can vary considerably between years. Although some Douglas-fir seeds are produced every year, abundant cone crops occur from 2 to 10 years apart. Other trees, such as maples and ash, produce some seeds almost every year. Seeds of certain species always are hard to find. For example, western larch seeds are always at a premium because even when good cone crops occur, problems with pollination and insect predation make seed collection almost impossible (Danielson and Riley 1995). In good seed years, collecting and processing can take several weeks or months to complete, and then seeds must be stored properly until they can be sown.

Seeds of some species store so poorly that nurseries must collect fresh seeds for each crop. For example, blue oak acorns must be harvested fresh-directly from the branches- because those on the ground already have desiccated, which greatly reduces seed quality. This species has an unusually wide 2-month collection window, however. As long as acorns were collected properly and not allowed to dry out, germination percentage was consistently over 90% throughout the period (McCreary and Koukoura 1990). All of which re-emphasizes the importance of knowing the basic biology of a species before attempting to propagate it.

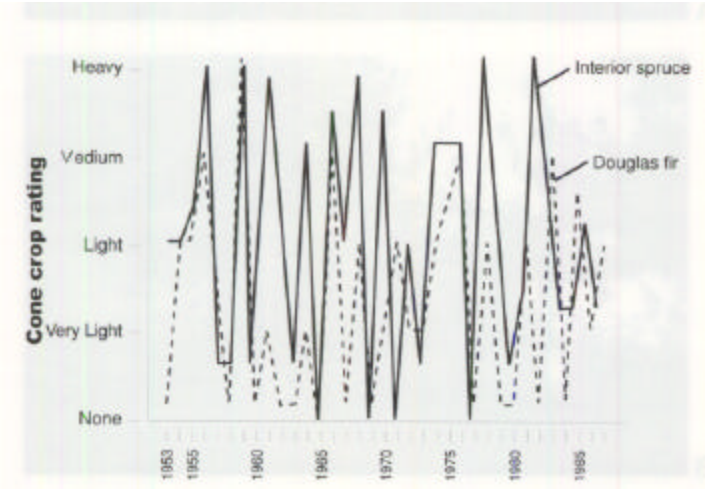


Figure 6.2.9—*Most forest and conservation species do not produce a good crop of seed every year as illustrated by the cone crop production patterns of these commercial conifers (modified from Eremko and others 1989).*

State and federal government nurseries usually do their own seed collection, processing, and storage and so are excellent sources of information for the novice nursery manager. (The subject of seed collection and processing is too complicated to cover in more detail here and so the reader is referred to the literature sources in section 6.2.11.)

6.2.2.2 Considerations when purchasing seeds

Many nursery managers grow seedlings from seeds have purchased from commercial dealers, or seeds often are supplied by the customer. As mentioned earlier, it is imperative to insist on the proper seed source when purchasing seeds and **it is a good idea to ask seed dealers which seed sources of a particular species they have in stock** rather than specify which source you want to purchase. Some unscrupulous dealers always seem to be able to come up with whatever seed source is needed if they want to make a sale badly enough. If you are a novice grower, then it might be a good idea to call other local nurseries to find out the names of reputable seed dealers. The USDA Forest Service's National Tree Seed Laboratory has published a handy reference called "Commercial suppliers of tree and shrub seed in the United States" (USDA Forest Service 1995). It is available in either hard copy or can be accessed on the Seedlings, Nurseries, and Tree Improvement home page on the World Wide Web:

» willow.ncfes.umn.edu/snti/snti.htm «

Next, always make sure that seeds have been tested for **quality.** In particular, a germination test, percentage purity, and seed weight will be needed to properly calculate seed sowing rate. If test data are unavailable on the desired source, then lower the price accordingly and adjust the projected sowing date until tests can be done. Tetrazolium tests are often done on forest and conservation species but are less accurate than standard germination tests. While it is possible to make an educated guess about seed viability from cut tests and oversow enough to compensate for the estimated variation, this is never recommended. Production space in container nurseries is just too valuable to gamble on seeds of unknown quality. There are no bargains-high quality seeds always are worth the price and the effort to locate them. (Seed testing is discussed in detail in section 6.2.3.)

The amount of seeds needed to grow a given number of seedlings will depend on the information from the seed tests (see section 6.2.8.1 for sowing calculations).

6.2.2.3 Upgrading seed quality

Nursery managers who purchase seeds should expect clean, pure seeds of high quality, but those who collect and process their own seeds may need to upgrade certain seedlots. Although it cannot directly improve the quality of individual seeds, upgrading improves the potential performance of a seedlot by removing empty, damaged, weak, and immature seeds.

Cleaning and upgrading seeds is a highly specialized art that cannot be discussed in adequate detail here. The most comprehensive information on woody plant seed collection and processing can be found in *Seeds of Woody Plants in the United States* (Schopmeyer 1974; Bonner, in press) and *Methods and Procedures for Testing Trees Seeds in Canada* (Edwards 1987). For a discussion of basic concepts and available equipment for processing conifer seeds, the reader is referred to the *Bareroot Nursery Equipment Catalog* (Lowman and others 1992) or the *Tree Seed Technology Training Course: Instructor's Manual* (Bonner and others 1994). More information on the collection and processing of broadleaf trees and shrubs is included in the *Hardwood Nursery Guide* (Williams and Hanks 1994) and *Collecting, Processing, and Germinating Seeds of Western Wildland Plants* (USDA Agricultural Research Service 1981) covers other native plants.

If nurseries are given seeds that need upgrading before they can be sown, the following techniques are useful.

Recleaning. Nurseries may have to reclean some seedlots before they can be sown, especially if precision seeders will be used. Although most nurseries typically do not have the full range of seed-cleaning equipment, there are some simple procedures to upgrade seedlots. The basic seed-cleaning machine is the air-screen cleaner, which uses a combination of screening and air flow to remove debris. A smaller "office version" is ideal for small upgrading jobs. Air-screen cleaners are relatively inexpensive and can be used to upgrade seedlots by 3 physical properties: size, shape, and density (Bonner and others 1994). Another simple and quick way to remove empty seeds for some species is by flotation-the principle is that heavier, filled seeds will sink in water and the lighter, empty or damaged seeds will float. This procedure needs to be checked carefully with a cut test, however, as some filled seeds will float if water bubbles are trapped on the seed coat and empty seeds may sink if they are dirty.

A promising new technique for upgrading pine and spruce seedlots is the IDS (Incubation-drying-separation) method, which separates filled nonviable seeds from filled, viable ones (Simak 1984). Seeds are soaked in water at 15 °C (59 °F) to obtain full imbibition, then dried at 25 °C (77 °F) to create differences in seed moisture content. During drying, viable seeds will retain more moisture than nonviable ones, so this difference in weight can be used to separate the two fractions by flotation in water (figure 6.2.10). The IDS method is still being evaluated and developed, but has promise as a simple technique to upgrade the quality of seedlots (Bergsten 1993). Operational work has shown that a lodgepole pine seedlot could be upgraded from 85% to 95% germination capacity by this technique. Sometimes, the poorer the seedlot, the greater the gain through IDS upgrading: a Douglas-fir seedlot that had been damaged during processing was raised from a germination capacity of 17% to 96% (Edwards 1993).

Sizing. Some species and seedlots show considerable variation in seed size and so there could be several advantages to sizing seeds, either with screens or by gravity, before sowing. The potential nursery benefits of seed sizing are (1) easier sowing with mechanical sowing equipment, (2) faster and more complete germination, and (3) more uniform seedling density, which translates into higher seed-use efficiency (Belcher and others 1984). A review of the literature found that seed size was significantly correlated with germination rate 50% of the

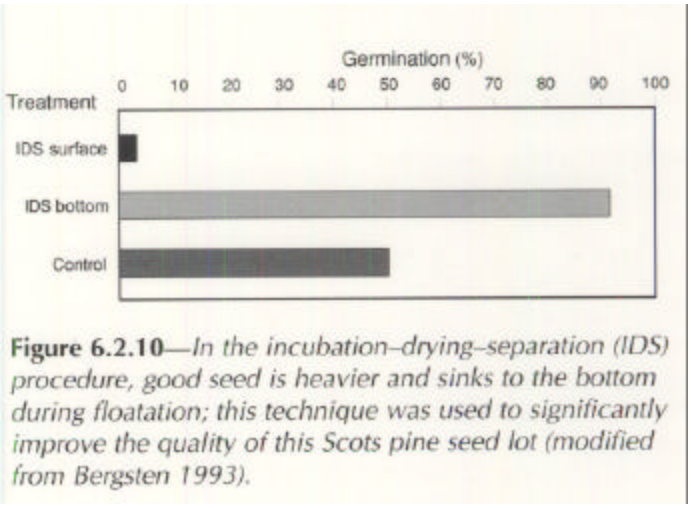


Figure 6.2.10—*In the incubation–drying–separation (IDS) procedure, good seed is heavier and sinks to the bottom during floatation; this technique was used to significantly improve the quality of this Scots pine seed lot (modified from Bergsten 1993).*

time and with seedling size 84% of the time (Bonner 1987). Some southern container nurseries routinely size their pine seeds and have found that medium to medium-large seeds produce the best seedlings (Barnett and McL.emore 1984). Trials with other tree species have not shown sizing to be operationally useful, however. Seed size was found to have no significant effect on seedling attributes of Douglas-fir (El-Kassaby and others 1992) or Sitka spruce (Chaisurisri and others 1994). Dumroese and Wenny (1987) found that, although larger western white pine seeds germinated faster and more completely, their final seedling heights and stem calipers were not significantly different than seedlings grown from bulk seed (table 6.2.3). Therefore, for the majority of forest and conservation species, seed sizing as a separate process is probably not worthwhile.

Table 6.2.3—*Sizing western white pine seeds improved germination compared to bulk seeds, but did not improve the final size of container seedlings*

Seed size class	Seeds/kg	Total germination (%)	Germination rate (days)	Seedling height (cm)	Stem caliper (mm)
Small	60,990 c	50 c	23 c	10.5 a	2.8 a
Medium	49,260 b	61 b	22 b	10.4 a	2.7 a
Large	39,073 a	71 a	19 a	11.9 a	3.0 a
Bulk seed	48,422 b	61 b	22 b	11.3 a	2.8 a

Source: Modified from Dumroese and Wenny (1987).
Different letters within columns indicate statistically significant differences at the $P < 0.05$ level.

6.2.3 Seed Testing

High seed quality is essential to consistently produce crops of superior seedlings, and the only way to determine seed quality is by testing. Although large container nurseries may perform some seed tests in-house, most nurseries use the services of commercial seed labs. Often, seed companies will have their seeds tested before offering them for sale, but in other cases, nursery managers may have to have the seeds tested themselves. To ensure that results are comparable, seed testing labs around the world follow the standard International Seed Testing Association procedures (ISTA 1985). These rules must be followed whenever seeds are exchanged or sold, because sale of tree seeds is regulated by law in some states and many foreign countries (Hartmann and others 1997). Nursery managers should note, however, that these highly regulated seed testing procedures may not apply to operational nursery conditions and should be prepared to modify them when appropriate. For example, the standard germination test is done under ideal conditions in a growth chamber. This may give a good indication of seed performance under fully controlled growing environments but may be poorly correlated with performance in an open growing compound.

Seed testing takes time, usually from 4 to 6 weeks. Therefore, managers should ask customers if their seeds have already been tested or must allow time to have the tests done before they can prepare them for sowing. Even if the nursery purchases all its seeds, managers should have a basic knowledge of the various steps of seed testing and understand the technical terminology so that they can communicate easily with seed suppliers and seed laboratory personnel. Make certain that labs are members of the Association of Official Seed Analysts (AOSA) to ensure that their testing procedures meet established guidelines. The National Tree Seed Laboratory can perform all types of seed tests or recommend another reliable laboratory:

USDA Forest Service National Tree
Seed Laboratory 5156 Riggins Mill
Road Dry Branch, GA 31020-9696
TEL: 912/751-3552 FAX:
912/751-3554 E-MAIL:
» seedlab@ix.netcom.com «
website:
» http-//willow.ncfes.umn.edu/seed-lab/ntsl-ol.htm «

The seed testing process can be divided into three sequential operations:

1. The seedlot must be sampled in a statistically valid manner so that tests reflect the true nature of the entire lot. 2. Tests of physical properties (moisture content, thousand seed weight, and purity) should be done before seeds are stored, and also are necessary to compute sowing rates. 3. Seeds should be tested for viability to give an estimate of how quickly and completely they will germinate, and how well they will grow after they are sown.

The actual testing can be divided into physical seed tests and viability tests. Physical seed tests are normally done only once, when the seedlot is first collected and processed, because the results do not normally change over time. Viability tests also should be conducted after seed is collected but, because seed quality will change during storage, viability of stored seedlots should be tested at intervals of every 2 or 3 years to assure that seed quality has not decreased significantly. Seeds of some species can be stored successfully for many years, whereas other must be sown immediately. (Seed storage is discussed in detail in section 6.2.4 of this volume.) Any seed test is only as good as the sampling technique that was used to select the test sample, and therefore the seedlot must be properly sampled.

6.2.3.1 Sampling

Collecting seed samples is extremely important for two reasons. First, the sample must be representative of the entire seedlot and second, seed testing laboratories require a certain amount of seeds to perform each type of test. The best seed-quality test can only apply to the seed sample submitted for analysis and therefore, if a sample does not truly reflect the characteristics of the entire seedlot, the test results are useless. A seedlot is defined as the entire quantity of seed of one species and ecotype from a particular location at a single collection date. Even within the same seed zone, seed quality changes between different locations and seed maturity changes over time, even from week to week. (See section 6.2.2 for further discussion of these terms.)

The definition of a seedlot will also depend on your objectives as well as the type of test that you are doing. During initial seed processing, the seedlot will consist of all the containers from that collection and so each con-

tainer must be sampled. After seeds have been stored, however, the sampling population may consist of only a portion of the total seedlot, depending on the objectives of the test. Most physical attribute tests, such as purity and weight, will not change over time and therefore the sampling population will always be the entire seedlot. However, as mentioned in the previous section, seed viability will change over time, so the sampling population must change with the situation. In the case where you have a large quantity of a particular seedlot in storage, you will only want a germination test on the amount of seed that you will be sowing for your current crop. For example, if you have 25 kg (55 lb) of ponderosa pine seed in storage but will be sowing only 5 kg (11 lb) this year, then you will treat this amount as a seedlot and test it separately. The remaining 20 kg (44 lb) of seed in storage will now constitute a separate lot and will have to be tested for viability again the next time it is used. Moisture content also changes when a batch of seed is removed from refrigerated storage for any amount of time. The purity and seed weight will remain the same for both seedlots, however.

Once the seedlot has been defined, it must be sampled systematically with appropriate techniques and tools. The proper sampling tools and procedures depend on the type of seeds and size of the seedlot. Free-flowing seeds, such as pines and chokecherry, are generally sampled with a hollow, partitioned probe called a "trier" (figure 6.2.11). The closed trier is inserted into the seed container on a diagonal plane and then opened to admit seeds simultaneously from different levels. Seeds with irregular shapes and those with wings, which includes many native shrubs, are usually sampled by hand. Insert your hand with open palm and fingers tight together and then scoop an equal amount of seeds from several locations in the container (Stein and others 1986). Large-seeded species, such as oaks and walnuts, are particularly difficult to sample so it may be necessary to pour them out of their storage container to obtain a representative sample. If the seedlot is stored in several containers, samples should be drawn from each container in at least five different positions in both the horizontal and vertical planes (Gordon 1992).

Seed analysts use standard terminology for the stages in the sampling and testing process and nursery managers should be familiar with these terms (Bonner and others 1994). "Primary samples" are collected from the entire seedlot and then mixed to form a "composite sample," from which a "submitted sample" will be sent to the testing laboratory (figure 6.2.12). The amount of seeds required for the full range of tests varies from 2,500 to

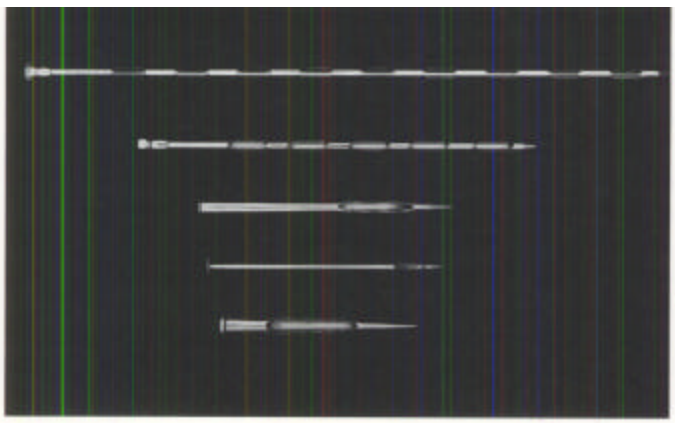


Figure 6.2.11—*A seed sampler, called a "trier," is used to collect a representative sample of conifer seeds from different levels of large storage containers (from Stein and others 1986).*

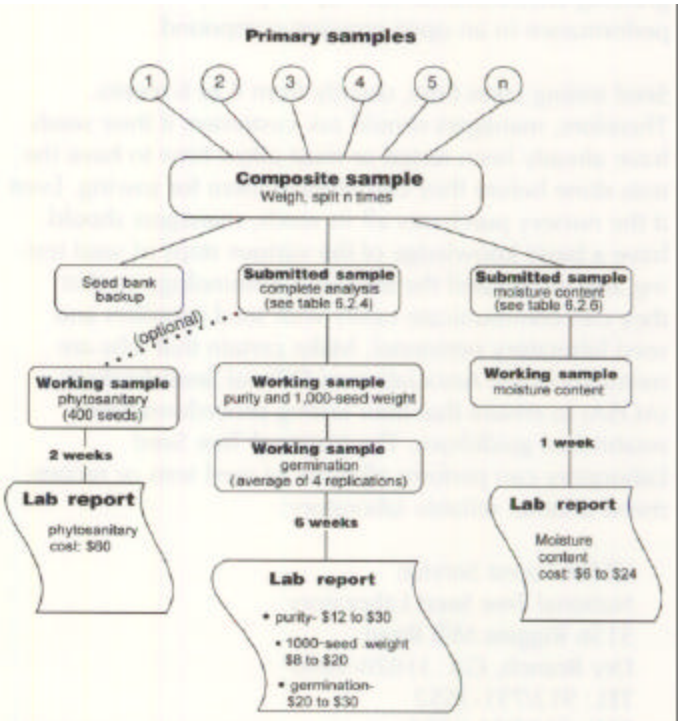


Figure 6.2.12—*Seeds can be tested for several quality attributes by collecting "primary samples" from the entire seed lot to make up a "composite sample" that is is further divided to form "submitted samples," which are sent to the testing laboratory (modified from Edwards and Wang 1995).*

5,000 seeds except for large seeded species for which 500 is sufficient. On a weight basis, the submitted sample will range from 25 to 240 g (0.9 to 8.5 oz) for most conifers but can range as high as 1 kg (2.2 lbs) for large seeded species (Cordon 1992). The amount of seed to submit also will depend on seed size and density and some typical submitted samples for a variety of forest and conservation species are provided in table 6.2.4. Requirements may vary between testing laboratories, however, and therefore it is always a good idea to contact them before sampling just to be certain.

All seed samples should be packaged in rigid containers to protect them during shipping, and sent to the testing lab by the quickest means possible. If moisture content will be taken, then seeds should be placed in a plastic bag to retard moisture loss. Species with high moisture contents may heat-up or mold during shipment, however, so samples should be kept out of direct sunlight and shipped promptly (Cordon 1992). Each seed sample must be accompanied by the following information:

- Full name, address, phone, and FAX number of sender
- Date of sampling and of original collection
- Species, seed source and any other specific identification information
- Quantity of seed submitted and of total seedlot
- Type of storage and storage temperature
- Time available for testing

if time is short before sowing, then the lab may recommend a quick estimate of viability instead of the standard germination tests, which will take at least 4 to 6 weeks. With species such as western white pine that have long stratification requirements, the tests can take 4 to 6 months.

Once it reaches the testing laboratory, the "submitted sample" is further divided into a "working sample" that is used for the various tests of seed physical characteristics and quality (figure 6.2.12).

6.2.3.2 Measuring physical attributes

The first measurements taken when the laboratory receives the seeds are moisture content, purity, and weight. Because seed moisture content can change rapidly, it is measured immediately.

Moisture content. Seed moisture content provide several types of valuable information to the nursery manager. It can indicate seed maturity, determine if the seedlot must be treated before storage, or indicate the type of presowing treatment to assure rapid and complete germination (Bonner and others 1994). In particular, nurseries must know the moisture content of seeds that they are going to store because seed quality can be rapidly lost if moisture content is outside the narrow range of 5 to 8% (table 6.2.5).

Table 6.2.5—*Seed moisture content thresholds and potential effects during storage*

Moisture content	Potential effects
> 30	Germination can begin
18–20	Respiration causes overheating
10–18	Fungi become active
> 9	Insects become active
5–8	**Best range for sealed storage**
< 5	Desiccation possible

Source: Modified from Bonner and others (1994).

Table 6.2.4— *Recommended submitted sample sizes for a "complete" seed analysis of purity, germination, and thousand-seed weight*

Species	Average no. of seeds		Submitted sample size	
	per kg	per lb	g	oz
Red alder	1,470,000	666,000	15	0.5
Rosegum eucalyptus	705,600	320,000	60	2.1
Black walnut	88	40	500 seeds	—
Sweetgum	180,800	82,000	30	1.0
Loblolly pine	40,130	18,200	140	4.9
Quaking aspen	7,940,000	3,600,000	5	0.2
Northern red oak	275	125	500 seeds	—
Black locust	52,920	24,000	100	3.5

Source: Modified from ISTA (1985).

The standard laboratory test for seed moisture content involves drying the seed sample in an oven and then calculating the weight of water lost. However, nurseries often want to obtain a rapid estimate of seed moisture content and so, for these operational tests, electronic moisture meters (figure 6.2.13) are used for small seeds of most commercial tree species. Several brands of seed grain meters can estimate tree seed moisture content within 1 % if they are calibrated against an ovendry standard. A list of suppliers of moisture meters can be found in Lowman and others (1992) and the National Tree Seed Laboratory can provide moisture charts for the major brands (see address in section 6.2.3).

Figure 6.2.13—*Electronic moisture meters can give quick measurements of seed moisture content if they have been properly calibrated for the species (courtesy of R. Karrfalt, USDA Forest Service).*

A microwave oven can be used to dry larger seeds if the procedure is done properly (table 6.2.6). If not, it can kill the seeds. Cover the seed sample during the entire procedure to make sure that seeds do not gain or lose moisture to the atmosphere. The moisture content (%) is calculated from the following formula (Edwards and Wang 1995):

$$\text{moisture content} = \frac{M_2 - M_3}{M_2 - M_1} \times 100$$

where: M_1 = weight of the empty container and cover
M_2 = weight of container, cover, and seeds before drying
M_3 = weight of container, cover, and seeds after drying

Note that seed moisture content is expressed as a percentage of water loss compared to the original fresh weight of seeds, rather than of the ovendry weight, which is the standard when the moisture content of soils is calculated (Stein and others 1986).

The next phase of the seed testing procedure involves seed that is sent to the lab for a "complete analysis," where one submitted sample is tested for purity, thousand-seed weight, and germination (figure 6.2.12).

***Purity*.** The purity test determines what proportion by weight of the sample is **pure seed** of the designated species and how much is impurities. The test is done by weighing enough seeds to make a working sample of approximately 2,500 seeds of most species, or 500 seeds of large-seeded species (Gordon 1992). The seeds are visually inspected and pure seeds are separated from 3 classes of impurities: seeds of other species, weed seeds, and inert matter. Some seeds of forest and conservation species retain all or part of a wing or integument after processing, and these require special attention. For example, the wings of Douglas-fir and ponderosa pine seeds should be removed during normal processing, whereas those of maples or mahogany should not. Nursery managers should realize that the pure seed component can still contain damaged seeds as long as they are larger than half the size of a complete seed (Bonner and others 1994). Thus, pure seed does not necessarily mean that a seedlot is also of high quality.

Pure seeds and each category of impurity is weighed and expressed as a percentage by weight of the total working sample. Good seed processing should always produce

Table 6.2.6—*The best method for obtaining a rapid estimate of seed moisture content depends on seed size and composition*

Seed size and class	Typical genera	Recommended method	Necessary sample size
Small/low oil content	*Platanus, Robinia*	Electric moisture meter	80–200 g
Small/high oil content	*Abies, Pinus, Tsuga*	Electric moisture meter	80–200 g
Large/low oil content	*Nyssa, Aesculus, Quercus*	Microwave oven	4–5 g or at least 5 seeds
Large /high oil content	*Carya, Fagus, Juglans*	Microwave oven	At least 5 seeds

Source: Modified from Bonner (1981).

95% purity for most commercial conifer seeds and higher purity (>99%) should be mandatory for seeds grown in container nurseries, especially those using precision seeders. Purity is much more difficult for many native plant seeds because of irregular seed shapes, sizes and appendages.

Weight. Seed weight is traditionally determined by weighing 1,000 seeds of the seedlot. A working sample for the **thousand-seed weight** analysis is taken from the same working sample as the purity test (figure 6.2.12). Most laboratories have seed-counting machines that can automatically count out and weigh 1,000 seeds. The analysis can also be done by hand: several replications of 100 seeds each are counted, weighed, and an average used to calculate the thousand-seed weight.

Seed weight is a function of seed size, moisture content, and proportion of full seed in a given lot, and so also gives an indication of seed quality. The thousand-seed weight is required for calculating sowing rates in bareroot nurseries but is less important in container facilities because sowing is done on a numerical basis-one or more seeds per container. The thousand-seed weight can easily be converted to **seeds per kilogram (or seeds per pound)** which traditionally is used to describe seedlots (table 6.2.4).

6.2.3.3 Testing seed viability and germination

Although the two terms are often used interchangeably, nursery managers must understand the difference between **viability** tests, which *estimate* the potential to germinate and grow, and **germination** tests, which *measure* their actual achievement. Viability can be estimated by several means, including the standard cut test, the tetrazolium test, and the excised embryo procedure. All except the latter are routinely used for nursery testing purposes. However, germination tests are the standard measure of seed quality in forest and conservation nurseries.

All the following tests assume that seed dormancy requirements have been met, but this often is not the case in actual practice. So, nursery managers must be familiar with the dormancy characteristics of the species that they wish to propagate, and either require that the seed dealer perform the necessary pretreatment, or allow time to do it themselves. (Presowing seed treatments are discussed in detail in section 6.2.5 in this volume.)

Cut tests. This traditional test should not be overlooked because it is a simple and quick way to estimate the viability of a seedlot. Using a sharp knife or single-edged razor, a sample of seeds is cut in half and the contents inspected under a hand lens. Cut tests reveal seeds that are empty, damaged, or insect-infested and also reveal abnormal morphology. Immature seed structures often identify seeds that have been collected too early. Of course, the normal structure of seeds of the crop species must be known for comparison (figures 6.2.1 to 6.2.6). Like all viability tests, however, a cut test will not show whether the seed lot will germinate because dormant seeds have normal morphology. The process of using cut tests to assess the quality of commercial conifer seeds is well described in *Anatomy and Morphology of Conifer Tree Seed* (Kolotelo 1997). This publication also includes color photographs of common seed problems and a key to classify seeds during cut tests.

Cut tests also can be used during and after presowing seed treatments to determine their effectiveness. For example, cut tests can be used to time cold-moist stratification. When the cotyledons of conifer seeds enlarge and turn light green, the seeds are near germination and should be dried down and stored under refrigeration until time to sow (Banerjee 1994).

Tetrazolium tests. The tetrazolium (TZ) test is the most popular seed viability test and can take only hours to complete. The chemical principle behind the test is that living seed tissue will stain bright red when treated with

the normally colorless solution of triphenyl tertrazolium chloride (figure 6.2.14). The TZ solution reacts with dehydrogenase enzymes that are present in all living tissue and form a reddish, insoluble compound called formazan.

The testing procedure is easy to do-a sample of seeds is cut in half lengthwise, TZ solution is applied, and the seeds examined with a hand lens. Because the staining reaction is affected by pH, temperature, time, and concentration of the TZ solution, standard laboratory conditions must be maintained during the test. Deeply dormant seeds require longer staining times, more concentrated TZ solutions, and special preconditioning treatments (AOSA 1995).

Although the TZ staining procedure is relatively easy to perform, the stained seeds require experience to interpret properly. Seed analysts consider several factors when evaluating a TZ test (Vankus 1997):

1. Amount of area that is stained
2. Intensity of staining
3. Pattern of staining
4. Turgidity of tissues
5. Presence and condition of essential seed components

Experience has shown that, with most seeds, tetrazolium results will often overestimate the actual germination percentage. There are also species differences, however. Oak acorns contain chemicals that inhibit the tetrazolium reaction, so these tests tend to underestimate the germination percentage (Gordon 1992). Other studies have reported excellent correlation between TZ and standard germination tests and that for some species, including maples and bitterbrush, the TZ test is a better reflection of actual nursery performance (Hardin 1981).

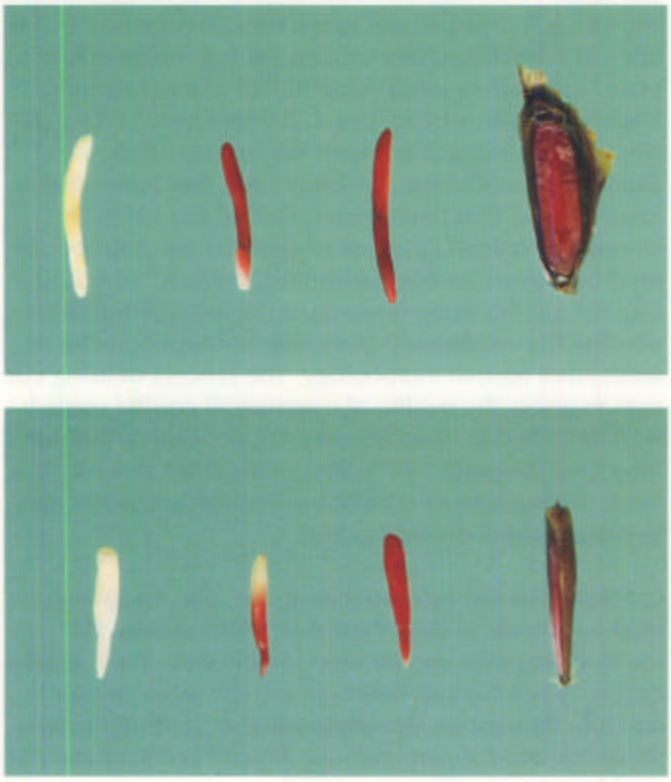


Figure 6.2.14— *Tetrazolium (TZ) tests stain living seed tissue red and can be used to give a quick estimate of seed viability: from right to left, good seed, healthy embryo, damaged embryo, and dead embryo (***A** *= noble fir;* **B** *= cliffrose (from Stein and others 1986).*

From a grower's standpoint, tetrazolium tests are commonly used when they are asked to sow a seedlot before a standard germination test can be completed. The TZ test is especially useful for determining the viability of very dormant seeds that would otherwise require long pretreatments before germination tests could be conducted (Stein and others 1986). TZ tests also are used to determine the viability of ungerminated seeds at the end of germination tests (Vankus 1997).

Whether to do TZ tests at the nursery or send them to a testing laboratory depends on several factors. Closely examining seed structures and learning about seeds of different species would be most valuable to any nursery worker. Vankus (1997) provides a complete listing of the equipment and supplies needed to do TZ tests and also provides addresses for obtaining training in the TZ procedure. However, the exact procedure for conducting TZ tests varies by family of plant (AOSA 1995) and interpreting the results requires experience. So, unless a large number of samples need to be tested, it usually is more cost-effective to work with testing laboratories.

X-ray analysis. Many seed testing laboratories and some nurseries now use X-ray radiography routinely, and interestingly enough, this is one of the few technologies that originated with tree seeds (Bonner and others 1994). The procedure consists of placing a sample of pure seeds on a tray and exposing them in the X-ray machine. The X-rays pass through the seeds, strike a photographic film,

and produce a black-and white photograph called a radiograph (figure 6.2.15). Many aspects of seed quality can be determined from analyzing these radiographs, including seed structure, embryo maturity, empty seeds, insect infestation, and seed coat injuries that are invisible to the naked eye (Stein and others 1986). Although it cannot measure viability, the X-ray procedure is a valuable adjunct to germination tests.

Germination tests. In most forest and conservation nurseries, the germination test is the best performance test of a seedlot and therefore is used as the operational test of seed viability. In a standard germination test, four replicates of 100 seeds each are placed on a moisture-retentive substrate under optimal environmental conditions of light and temperature. Seed testing laboratories conduct the tests under sterile conditions in special germination chambers (figure 6.2.16A/B), and count the number of seeds that have germinated on a weekly basis for 4 weeks (table 6.2.7). Because of differences in seed dormancy, not all forest and conservation seeds can be tested in the same manner, and some require pretreatment. A list of recommended procedures for tree and shrub seeds can be found in the international Rules for Seed Testing (ISTA 1985). For example, maple seed embryos must be excised and honeylocust seeds must be scarified before testing. For species with complex dormancy requirements, such as rose, the tetrazolium test is prescribed instead of a germination test. (See section 6.2.5 for a full discussion of seed treatments.)

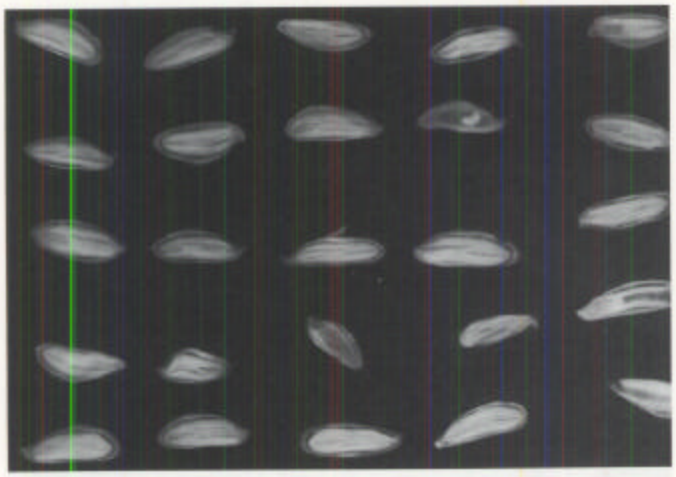


Figure 6.2.15—*X-ray radiographs provide quick, nondestructive measurements of seed quality, showing hollow seeds and those infested with insects (from Stein and others 1986).*

The evaluation procedure for germination tests is also standardized. To be counted, seeds must germinate normally and exceed some standard growth stage such as "having a radicle four times as long as the seed coat." The average number of seeds from the four replications that germinate normally is reported as the **germination percentage** or **germination capacity.** Seeds that failed to germinate are usually given a cut test to make sure that they are filled and healthy. These cut test data are report-

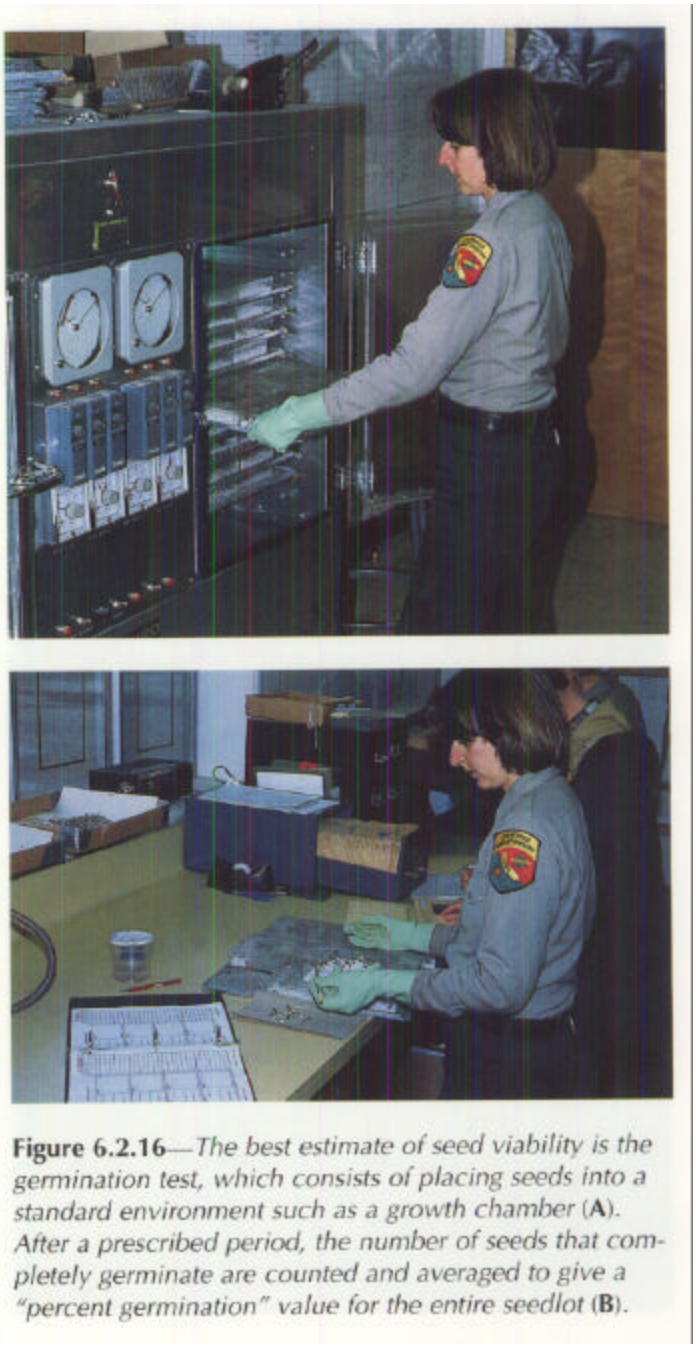


Figure 6.2.16—*The best estimate of seed viability is the germination test, which consists of placing seeds into a standard environment such as a growth chamber* (**A**). *After a prescribed period, the number of seeds that completely germinate are counted and averaged to give a "percent germination" value for the entire seedlot* (**B**).

ed in addition to the germination percentage (table 6.2.7) and they give the nursery manager an indication of how well the seedlot was processed and the degree of seed dormancy (Gordon 1992).

Speed of germination is another important result of the germination test, and so many testing laboratories report germination results by week. By plotting the germination percentage over time, nursery managers can observe the rate of germination, a good indication of vigor. Species or seedlots that show significant variation in germination rate may need different presowing treatments. For example, the standard 3-week cold-moist stratification treatment was shown to be inadequate for a mixture of Douglas-fir seedlots (Edwards and El-Kassaby 1995).

Many germination indices have been developed and some have practical application in container nurseries (Bonner and others 1994):

Peak germination = the specific time at which germination is highest.

Germination energy = the proportion of germination that has occurred up to the time of peak germination.

Other terms such as germination value and peak value (Czabator 1962) are mathematical expressions that are sometimes reported in research reports but are not normally used in operational nursery practice. A complete discussion of terms used by seed testing laboratories and good photographs of normal and abnormal germinants for many tree seeds can be found in Edwards and Wang (1995) and Kolotelo (1997).

Most nurseries grow a variety of species and seedlots, so that running a complete battery of germination tests each year can be relatively expensive (figure 6.2.12). Inexperienced nursery managers, or growers who have waited until the last minute, are often tempted to skip germination tests and oversow instead, but this is not a good idea. There is just too much variation in the performance of seeds of forest and conservation species and the waste of seed, the high labor costs of thinning, and the growth loss of overcrowded seedlings will far exceed any perceived cost savings (figure 6.2.17). We recommend that growers always insist on current seed germination tests when first contacted to grow a crop and require them in contract specifications. Allowing enough time in the crop schedule for seed pretreatments and testing is the mark of an experienced nursery manager.

Table 6.2.7—*These data from actual seed germination tests demonstrate that proper interpretation requires a combination of a knowledge of seed physiology and practical experience: lodgepole pine seed required prechill (cold-moist stratification) for optimal germination but this treatment seriously lowered viability for white spruce*

Species & prechill status	Days	Percent germination	Firm seed (cut test)
Lodgepole pine			
No	7	43	
	14	81	
	21	83	
	28	84	7
Yes	7	85	
	14	97	
	21	97	
	28	97	0
White spruce			
No	7	0	
	14	74	
	21	83	
	28	84	4
Yes	7	1	
	14	32	
	21	32	
	28	32	0

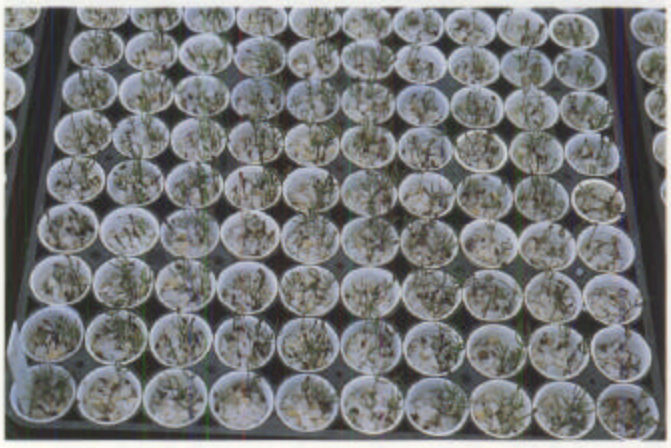


Figure 6.2.17—*Lack of good germination information on a seedlot can cause oversowing, which not only wastes seed but increases thinning costs.*

New tests. Probably the most promising is a nondestructive test termed leachate conductivity. Seeds are soaked in water for 24 hours at room temperature and then the electrical conductivity of the leachate is measured and related to seed quality (Barnett 1985a; Bonner and Vozzo 1983). The increase in conductivity of the leachate results from leakage of cellular substances as the cell walls deteriorate or are damaged. Commercial equipment is now available to speed and standardize the testing, and preliminary evaluations show considerable potential with southern pine seeds (Bonner and Vozzo 1986). Advantages are speed, ease of operation, and objective evaluation, but the equipment is costly and there still are unknown factors that affect measurements. Further research is needed to clarify these problems.

6.2.3.4 Interpreting germination tests

Standard laboratory germination tests must be properly interpreted before they can be applied in the nursery. Many forest and conservation species have dormant seeds, which must be treated prior to testing, and so the germination test may not reveal the true potential of the seedlot. The degree of dormancy can vary considerably within a species; for example, in pines, the length of the cold stratification treatment between varieties, ecotypes, or even seedlots (Krugman and Jenkinson 1974). Some laboratories conduct paired germination tests of both normal and cold stratified (prechilled) seeds (table 6.2.7). For seedlots that have unusually low germination percentages, nursery managers should request tetrazolium tests or X-ray analysis to try and determine the cause of the poor performance. (See section 6.2.5 for a complete discussion of dormancy.)

Remember that a germination test is an average of potential seed viability and that actual performance in the nursery may vary considerably. This has been well illustrated in research trials but also is evident to nursery managers in operational sowings, sometimes tragically (figure 6.2.17). Although presowing treatments can reduce it, some inherent variation in germination will always be present in forest and conservation seedlots (figure 6.2.18) and is actually desirable from a genetic standpoint (Campbell and Sorensen 1984). Nursery managers must realize that maintaining or even increasing biodiversity is a primary objective of many forest and conservation outplanting projects, and therefore they must expect some variation in germination performance. This is in marked contrast to most horticultural seeds which are hybrids that have been bred to germinate quickly and uniformly (Hartmann and others 1997).

Germination conditions in the nursery can be considerably different from laboratory tests (table 6.2.8). This is especially true in minimally controlled propagation environments such as open growing compounds. In these situations, the rate of germination should be given more attention. Frequently, even if seed testing shows that total germination is excellent, a relatively slow germination rate indicates that there may be a problem with nursery

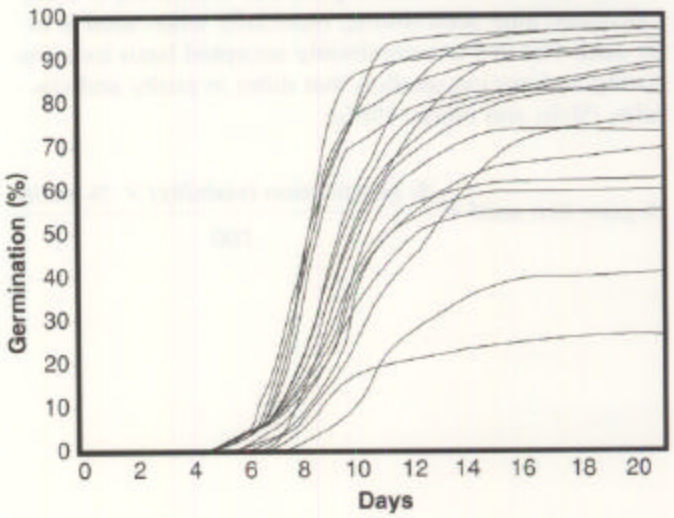


Figure 6.2.18—*Seed quality can vary considerably between seedlots collected the same year, as evidenced by these germination tests of different families of Douglas-fir (modified from El-Kassaby and others 1992).*

Table 6.2.8—*Laboratory germination tests are a reasonably accurate way of predicting actual seed germination in the nursery for most commercial tree species*

	Percent germination		
Tree species	Standard test	Presowing	Actual nursery
Douglas-fir	92	94	90
Interior spruce	85	88	86
Lodgepole pine	93	94	93
Ponderosa pine	84	80	84
Subalpine fir	62	58	51
Western white pine	80	60	68

Source: Modified from Kolotelo (1994).

performance. For many dormant species, a 30-day cold-moist treatment is recommended, but even longer periods of treatment may increase the speed and uniformity of germination under less than ideal conditions (Dunlap and Barnett 1982). Nursery managers should also utilize the experience of seed analysts at the testing laboratory to answer questions about test results because such efforts will be rewarded with marked improvements in seedling establishment and growth.

6.2.3.5 Computing pure live seed

A seed quality index called **pure live seed (PLS)** is often calculated after seed testing, especially when seed is to be sold. The PLS is a commonly accepted basis for comparing and pricing seedlots that differ in purity and viability (Stein and others 1986):

$$\% \text{ pure live seed} = \frac{\text{germination (viability) X \% purity}}{100}$$

Nursery managers should always insist on seed of the highest quality. Although seed dealers may offer seedlots with poor PLS values at bargain prices, this is a false economy that will be reflected in operational problems in the nursery. If the low-quality seeds belong to the nursery, then they should be sown immediately or destroyed because these seedlots deteriorate over time and have poor storage potential even under the best conditions. Conversely, high-quality seedlots will perform well over a wide range of environmental conditions and many can be stored for future seedling production (Edwards and Wang *1995).*

6.2.4 Seed Storage

Most container nurseries only need to store seeds for short periods of time, such as from the time of collection or purchase until sowing. Sometimes, however, more seeds are collected that can be immediately used or it may be more economical to buy larger quantities of a popular seedlot and store it from one year to the next. Successful storage requires knowledge of the seed characteristics of different species, high initial seed quality, and proper seed moisture content. Storage temperature, container and method also are important. The subject of seed storage is discussed in detail in Gordon (1992) and Bonner (1990).

6.2.4.1 Classes of seed storability

Longevity of seeds is a characteristic of the plant species, and there are four classes of seeds based on their genetics and composition (Bonner and others 1994):

1. **True orthodox**---seeds that tolerate desiccation and therefore store easily for relatively long time periods.
2. **Suborthodox**---seeds that require the same storage conditions as true orthodox seeds but have limitations due to seed composition and genetic origin.
3. **Temperate-recalcitrant**---seeds that are intolerant of desiccation so must be stored above freezing, and also must not be stored in airtight containers.
4. **Tropical**---recalcitrant seeds that have the same moisture and gas exchange requirements as temperate-recalcitrant species but in addition are very sensitive to low temperatures.

Other seed characteristics also affect storability. Thick or hard seedcoats restrict moisture loss, and seeds containing oils tend to be harder to store than those containing more starch. Seeds collected before they are mature or those that were under environmental stress during maturation store poorly.

Seed handling before storage will also affect storage potential. Exposing seeds to direct sunlight or high temperatures, especially at high seed moisture contents, is damaging. The care with which fruits and seeds are handled and stored during collection, shipping, and processing is important. Careless processing can cause cracks in the seedcoat or even bruise sensitive seed tissues. A cracked seedcoat allows moisture to escape and provides an entry for fungal pathogens.

6.2.4.2 Critical storage conditions: moisture content and temperature

Of all the factors that influence seed storage, moisture content is by far the most important. The recommended seed moisture contents for storing true orthodox and suborthodox species is 6 to 10% (table 6.2.9). For recalcitrant species, however, the moisture content must be maintained in the 30 to 45% range for storage periods of even a few years. Seed moisture contents also can affect the amount of undesirable secondary dormancy that develops during storage. Studies have indicated that moisture contents of 10 to 18% (dry-weight basis) during a 1-year storage period increased the degree of dormancy compared to that of seeds with moisture contents below 10% or above 18% (McLemore and Barnett 1968).

Temperature is the other important consideration when storing seeds. In general, the lower the temperature, the slower the seed deterioration rate, although the recommended range is considerably different between orthodox/suborthodox and recalcitrant species. Most seeds can be stored at temperatures at or slightly below freezing for short time periods except for those in the tropical recalcitrant category. These seeds are very sensitive to chilling injury which occurs at relatively cool temperatures of 12 to 20 °C (54 to 68 °F) (Bonner and others 1994).

Refrigerated storage is recommended for seeds of all but tropical-recalcitrant species whenever it can be economically justified and a reliable power source is available. Prefabricated modular refrigeration units are commercially available and make ideal seed storage structures. They can be free-standing or installed within existing buildings. Humidity control is not needed for orthodox and suborthodox seeds but is desirable for recalcitrant species. Because frost-free refrigeration units constantly remove moisture from the storage environment, all types of seeds must be packaged properly to maintain the proper moisture content. (See section on refrigerated storage structures in section 1.3.5.4 in volume one of this series.)

6.2.4.3 Storage containers

Seed storage containers must be rigid enough to provide physical protection during storage and handling. Containers that retard moisture loss should be used for storage of true orthodox and suborthodox seeds to pre-

Table 6.2.9—*Recommended storage conditions for the four classes of tree seeds*

Seed class	Storage period (yrs)	Seed moisture (%)	Temp. °C	Temp. °F	Container type	Example of typical genera
True orthodox	< 5	6–10	0–5	32–38	Airtight	*Pinus, Picea, Betula, & Prunus*
	> 5	6–10	− 18	0	Airtight	*Eucalyptus, Acacia, & Casuarina*
Suborthodox	< 5	6–10	0–5	32–38	Airtight	Seeds with high lipid content *(Juglans & Carya)*; seeds with thin seedcoats *(Populus & Salix)*; seeds that must be dried slowly *(Fagus & Citrus)*
	> 5	6–10	− 18	0	Airtight	
Temperate-recalcitrant	< 3	30–45	− 1 to − 3	26–30	Unsealed plastic bag	Seeds with high lipid content *(Quercus)*; seeds with high carbohydrate content *(Aesculus)*
Tropical-recalcitrant	< 1	30–45	12–20	54–68	Unsealed plastic bag	*Shorea, Hopea, & Dipterocarpus*

Source: Modified from Bonner and others (1994).

vent desiccation. Plastic bottles with screw tops (figure 6.2.19), and fiberboard drums or cardboard boxes lined with plastic bags have been used. Although rectangular containers are more space efficient, round ones assure necessary air spaces. Cardboard or fiberboard containers should be lined with plastic bags. Bags of 0.102 to 0.152 mm (4 to 6 mils) thickness are sufficient except in humid environments where thicker ones are used to maintain the desired seed moisture content. The recalcitrant species must have constant gas exchange, however, and so should be stored in containers lined with an unsealed 0.102-mm (4-mil) plastic bag (table 6.2.9).

6.2.4.4 Seed longevity in storage

Under natural conditions, most conifer and hardwood seeds have a life span of less than 3 years. When conditions are carefully regulated in refrigerated storage, however, viability of orthodox and suborthodox species can be maintained at high levels for much longer (table 6.2.10). Operationally, commercial conifer seeds are stored from 10 to 20 years with little appreciable loss in viability. The potential longevity of pine seeds under optimum moisture and temperature conditions is unknown, but it could approach 100 years (Bonner 1989).

Recalcitrant species can be stored for a much shorter period, ranging from a few months to a couple of years (table 6.2.10). The actual length of storage can vary with-

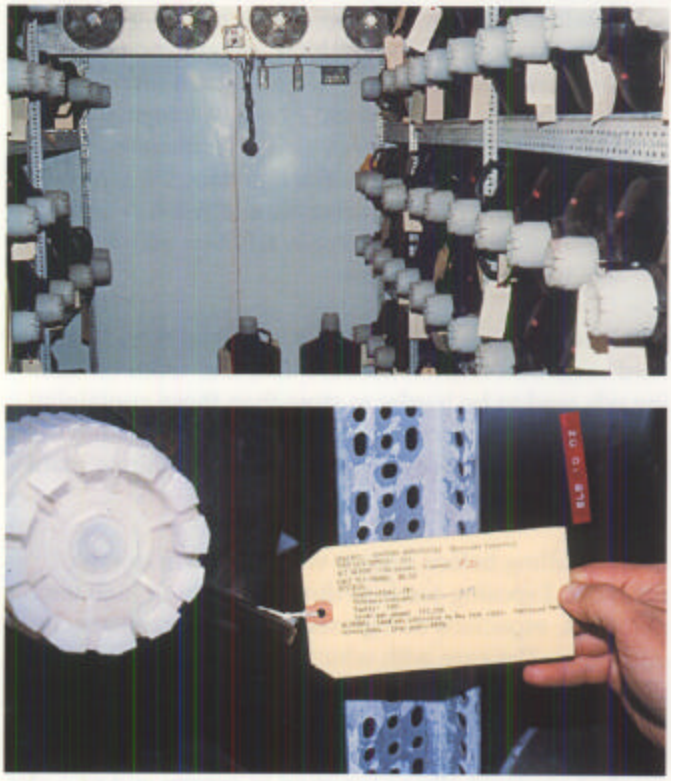


Figure 6.2.19— *Seed storage containers must provide physical protection, yet maintain the proper moisture content. Storage labels must be legible, permanent, and contain all the necessary seed lot identification information.*

Table 6.2.10—*Typical tree seed storage periods*

Seed class & species	Temperature °C	Temperature °F	Moisture content (%)	Time stored	Viability loss (%)
True orthodox					
Sugar maple	−10	14	10	5.5 yrs	5
Sweetgum	3	37	5–10	9.0 yrs	3
Ponderosa pine	0	32	8	7.0 yrs	0
Suborthodox					
European beech	−10	14	10	5.0 yrs	34
Eastern cottonwood	−20	−4	6–10	6.0 yrs	21
Willows	−10	14	6–10	1.2 yrs	0
Temperate-recalcitrant					
Silver maple	−3	26	50	18 mon	8
Southern red oak	3	37	35	30 mon	6
Northern red oak	−2	28	38–45	17 mon	18–46
Tropical-recalcitrant					
Araucaria hunsteinii	19	66	25–30	54 days	30
Philippine mahogany	14	57	40–50	30 days	60

Source: Modified from Bonner (1990).

in a genus, however, and oaks are an interesting example. When some white oak acorns are collected, the radicles are already emerging whereas some red oak acorns can be kept for up to 5 years when handled and stored properly. Some cultural treatments can extend the storage of acorns, such as soaking them in water for 48 hours at 2 °C (36 °F) before storing them in loosely tied plastic bags (Gosling 1988).

6.2.5 Presowing Treatments To Overcome Seed Dormancy

Unlike seeds of horticultural crops, which have been bred to germinate immediately after sowing, those of many forest and conservation species become dormant after they mature. **Seed dormancy** refers to a physiological state in which otherwise viable seeds will not germinate even when placed in growth-conducive environments (Bonner and others 1994). Dormancy is an ecological adaptation that ensures that seeds will only germinate when weather conditions, especially moisture and temperature, are favorable to the survival of the seedling. The **type of dormancy** is genetically controlled and so is usually the same for a given species or even genus. As with most things in nature, however, there are always exceptions and oaks are a good example. Most species in the red oak group have immature embryos that benefit from stratification, whereas most species in the white oak group do not. Within each group, though, there are oak species that are exceptions to the rule (Schopmeyer 1974). The **degree of dormancy** varies between ecotypes of a species, seedlots collected in different years, or even between individual seeds from a given plant. This variation is an adaptation that ensures that not all seeds will germinate at the same time but that some will germinate each year over an extended period.

6.2.5.1 Types of dormancy

Seed dormancy can be caused by several different factors, and there is no universal agreement on the best terminology for the types of dormancy. For it to be relevant to nursery managers, a dormancy classification system should be both logical and operationally useful (table 6.2.11). The major types of dormancy can be overcome with the following seed treatments. In the case of secondary dormancy, the best solution is preventing the condition in the first place by proper seed handling and storage.

6.2.5.2 Seeds without dormancy

Not all forest and conservation seeds are dormant; however, even nondormant seeds still need some treatment before they can be sown. Seeds that have just finished being processed or that have been in storage have lower moisture contents than is ideal for germination (table 6.2.5). **Imbibition** is the physiological process by which seeds absorb the water necessary to start the metabolic reactions that lead to germination. In nursery practice, this is achieved by soaking seeds in water for 24 to 48 hours. A running water rinse is recommended to keep the dissolved oxygen content of the water high and avoid stagnated conditions. Some nurseries even use a bubbler in the soaking tank. In addition to achieving imbibition, this treatment also softens the seedcoat and cleans it, removing possible chemical inhibitors or pathogens. (Seed cleansing and disinfection are discussed in section 6.2.7.)

6.2.5.3 Seedcoat dormancy

This condition is often called **external dormancy** because the restricting factor is the tissue surrounding the embryo (table 6.2.11). The degree of seedcoat hardness varies between species but also depends on the ecotype and weather conditions during the seed ripening process (Macdonald 1986). Several treatments can be used to soften the seedcoat but the best choice will depend on the cost and availability of materials and labor. Working with honeylocust and black locust seeds, the best scarification treatment was found to depend on the size and economic resources of the nursery (Singh and others 1991). The objective is to increase the permeability of the seedcoat to water and gases. Overly severe treatments may injure the embryo, so the gentlest method should be tried first, and then more severe treatments can follow until the seedcoat is permeable (Bonner and others 1994). **Keeping accurate and detailed notes of the treatment method and timing allows nurseries to develop a seed treatment guide for each species or ecotype.**

***Hot water soaks*.** This is the traditional treatment for many legume seeds or those with waxy seedcoats. A volume of water that is approximately 4 to 6 times the volume of dry seeds should be brought to a boil. Then, the seeds are immersed for a few minutes and the container is removed from the heat and allowed to cool. The embryo of some seeds can be damaged by high temperatures and so for these species, the water should be heated to only 65 to 70 °C (149 to 158 °F). Seeds can be removed and dried when they swell and become gelatinous to the touch. With some species, such as boxwood, imbibed seeds sink to the bottom of the container and floaters are removed and retreated. Although some growers use a standard treatment time for the hot water soak, it is better to experiment with each species and seedlot because of the variation in seedcoat thickness. Treated seeds are subject to bacteria and fungus infection and so should be sown within a few days. One problem with hot-water-treated seeds is that they stick together, making them difficult to use in mechanical seeders. One remedy for this is to place treated seeds in moist peat moss for a few days (Macdonald 1986).

Table 6.2.11—*Seed dormancy can be caused by several different factors*

Dormancy class	Causal factors	Examples of typical genera
Seedcoat (external)	1. Seed is impermeable to water or oxygen 2. Seedcoat physically restricts developing embryo	1. Many legumes: *Acacia* spp.; *Robinia* spp. 2. *Pinus* spp.; *Quercus* spp.
Embryo (internal)	1. Inhibiting substances within the embryo or surrounding tissue 2. Physiological immaturity	1. *Betula* spp.; *Magnolia* spp. (see table 6.2.2) 2. Eastern redcedar
Morphological	Embryo is not completely developed	*Fraxinus* spp.; *Pinus* spp.
Double	Embryo dormancy in both the radicle and epicotyl	*Prunus* spp.; *Quercus* spp.
Combined	Results from 2 or more primary dormancy factors	*Tilia* spp. have a very hard seedcoat plus embryo dormancy; *Crataegus* spp.
Secondary	Results from poor seed collection, handling, or storage	Loblolly pine after exposure to high temperatures and moisture during storage

Sources: Modified from Bonner and others (1994) and Macdonald (1986).

Soaking seeds in aerated water at 16 °C (60 °F) is a simple treatment for overcoming the mild seed dormancy of southern pines. It is particularly useful when there is not enough time for the traditional cold-moist stratification treatment (Barnett 1971).

Fire or Smoke. Dry-heat treatments are seldom recommended for overcoming seed dormancy because of the danger of embryo damage. A fire treatment, however, has been used on the seeds of some woody shrubs (for example, manzanita) from fire-dependent plant communities like the chapparral of southern California (Emery 1988). Obviously, this treatment should be done outside in a safe area. Eucalyptus seeds are sown in flats and covered with 6 mm (0.25 in.) of soil, topped with a layer of straw. The straw is then ignited and allowed to completely burn, and the dry heat breaks down the seed coat (Macdonald 1986). This fire treatment is not an exact procedure, however, because the amount and duration of the heat that reaches the seed cannot be accurately controlled.

The use of smoke to stimulate seed germination of fire-adapted native plants was discovered less than 10 years ago in Australia. Since then, researchers have demonstrated that smoke from the combustion of plant materials could positively affect the germination of 170 different species representing 37 plant families and 88 genera (Roche and others 1997). Both direct exposure to smoke and imbibition in dilute aqueous smoke solutions were effective but exposure times varied considerably between species. Some plants responded only after traditional seed treatments such as mechanical or acid scarification and others needed to have their seed stored in soil prior to treatment. Although the practical application of this technology still needs to be developed for North American species, the use of smoke as a pre-sowing seed treatment holds considerable promise for plants of fire-adapted plant communities such as the chaparral of Southern California.

Scarification. The process of **scarification involves** weakening the hard seedcoat just enough to allow imbibition, and several techniques are effective.

Mechanical abrasion. Seedcoats of small quantities of relatively large seeds can be treated by hand: nicked with a triangular file or sharp knife (figure 6.2.20), rubbed against coarse sandpaper, or burned with an electric soldering iron or wood-burning tool. This last

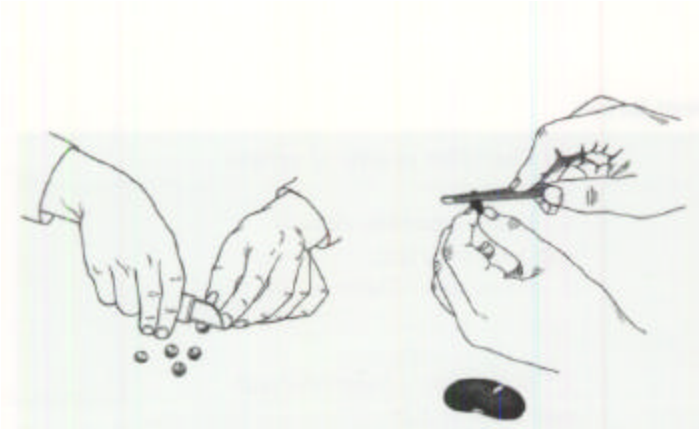


Figure 6.2.20—*Mechanical scarification. Large seeds with hard seed coats can be hand scarified with a sharp knife or a triangular file (modified from Bir 1992).*

"hot wire" technique is particularly handy because it makes a small hole in the seedcoat allowing the treated seeds to be shipped or even stored without lost viability (Bonner and others 1994). Workers should always wear protective gloves and can hold small seeds with tweezers. Mechanical scarifiers can be homemade or commercially purchased. To treat large seedlots, a rotating drum lined with sandpaper or a cement mixer filled with gravel has been used. Bunchberry seeds can be scarified by placing them in a rock tumbler with 120-grit sand for 5 to 7 days (Date 1994). Macerating berries in a modified household blender can be an effective mechanical scarification technique. Dull the blades with a file and blend the fruit in 2 to 5 volumes of water. This treatment lightly nicks the seed coat, improving imbibition and germination (Trindle 1995). Whatever technique is used, it is important to regularly check the seedcoats to make sure that the treatment has not gone too far.

Acid soaks. Another scarification method is to soak the seeds in a strong acid solution. Concentrated sulfuric acid (specific gravity of 1.84) is preferred but growers must be aware that this is an extremely caustic material and that worker safety always must be a foremost consideration (table 6.2.12). When properly done, acid scarification is a very effective way to remove hard seedcoats and stimulate quick germination (figure 6.2.21).

Seeds should be clean and dry. They should not be used directly out of cold storage because they may be covered with condensed moisture. After placing seeds in the treatment container, the acid is slowly poured over them, and they are left to soak for a period of 15 to 120 minutes. Because the treatment time will vary considerably between species and seedlots, it is a good idea to conduct some small-scale trials first by removing a few seeds at regular time intervals and cutting them to assess the thickness of the seedcoat. Another testing procedure is to divide the seed sample into several smaller batches, and then treat each for an increasing amount of time. The scarified seeds are soaked in water for several days and examined. The test batch with the highest proportion of

Table 6.2.12—*Safety and environmental precautions when handling acids*

1. Proper training is essential. All new employees should be trained on-site; experienced workers should receive "refresher" training each time they work with acids.
2. Full protective clothing must be worn to protect eyes and skin—acid-resistant rubber gloves and apron, eye goggles, and rubber boots.
3. Acid-resistant glass containers must be used, and the container should be much larger than the volume of seed to be treated.
4. **Water must not be added to acid—it will boil and splash back on the worker. Instead, the acid should be carefully poured into the larger volume of water.**
5. After the treatment, the acid solution must be diluted to safe concentrations by slowly pouring it into a large volume of clean water.

Source: Modified from Macdonald (1986).

Figure 6.2.21—*Acid scarification. Seeds with hard seedcoats, like these of squawbush, are treated with acid, which dissolves the seedcoat allowing water to penetrate and germination to begin (courtesy of N. Shaw, USDA Forest Service).*

undamaged swollen seeds indicates the optimum treatment time for that seedlot and species (Schopmeyer 1974). With *Arctostaphylos nevadensis seeds,* Trindle (1996) found that seed coat thickness was not a reliable guide for determining the optimum acid scarification timing and recommended checking the appearance of the endosperm itself. A glassy, water-soaked appearance indicates that the treatment has gone too far.

Macdonald (1986) presents a good operational procedure for acid scarification:

1. Place one volume of seed in a clean, dry container, and carefully add twice that volume of acid. Some growers put the treatment vessel in another container of cold water to reduce the resultant heat buildup.
2. Stir the seeds at regular intervals to prevent them from sticking to one another and ameliorate the heat buildup in any one location.
3. While the seeds are soaking, fill another container of equal volume with a 5% solution of sodium bicarbonate (baking soda) to use as an acid neutralizer bath
4. When the treatment time is completed, carefully pour off the acid, move the seeds to the neutralizing bath and stir.
5. Remove the seeds from the neutralizer and rinse them thoroughly in clear, cold water.

Although acid scarified seeds can be stored for a few days, it is best if they are sown immediately. Scarification of some species can be satisfied by either hot water or acid treatment (table 6.2.13). The best scarification treatment will depend on the requirements of the species and the skill and experience of the grower.

6.2.5.4 Embryo or morphological dormancy

These "internal" types of dormancy can have two different causes (table 6.2.11), but in both, the cultural treatment must overcome a physiological or morphological condition within the seed itself. As was the case with seedcoat dormancy, the degree of dormancy can very considerably from species to species and between ecotypes, and so again, the need to try different treatments and keep accurate and detailed records cannot be overemphasized.

Cold-moist stratification. For commercial forest tree species, stratifying seed under cold and moist conditions is the most common treatment to overcome seed dormancy. Cold-moist stratification originated from the historical practice of placing layers of seeds between alternating layers ("strata") of moist peat or sand. The current procedure of placing imbibed seed in plastic bags under refrigeration can be more accurately described as moist

Table 6.2.13—*Seed treatments to overcome dormancy for some typical forest and conservation species*

Species	Scarification		Stratification (days)		
	Hot water	Acid	Warm-moist	Cold-moist Fresh	Cold-moist Stored
Vine maple	No	No	30–60	—	90–180
Red maple	No	No	No	No	No
Sugar maple	No	No	No	—	40–90
Snowbrush ceanothus	Yes	No	No	—	90
Eastern redbud	Yes *	Yes *	No	—	30–60
Honeylocust	Yes *	Yes *	No	No	No
Rocky Mtn. juniper	No	No	120	—	120
Arizona pine†	No	No	No	No	No
Ponderosa pine‡	No	No	No	No	30–60
Loblolly pine	No	No	No	30–60	30–60
Quaking aspen	No	No	No	No	No

Source: *Schopmeyer (1974).*
* Either treatment will work.
† *Pinus ponderosa* var. *arizonica.*
‡ *Pinus ponderosa* var. *ponderosa.*

prechilling or naked stratification. Although prechilling is the term preferred by seed scientists, **stratification** will be used in this book because it is simple, definitive, and deeply ingrained in operational nursery vernacular.

Cold-moist stratification satisfies several important physiological functions, including activating enzyme systems and converting starches to sugars for quick metabolism. Although the exact mechanism is unknown, stratification also changes the balance between chemical inhibitors and promoters and so acts as a "switch" to chemically stimulate germination. Even in species that do not exhibit true dormancy, cold-moist stratification produces faster, and more complete germination (Moreno 1985). Cold-moist stratification also benefits biodiversity because it allows more individual seeds to germinate at the same time. For example, a mixture of unstratified Douglas-fir seeds showed highly significant variation in date of germination compared to those that had undergone cold-moist stratification (figure 6.2.22A) Seeds of some pines will germinate without stratification when freshly collected but dormancy will develop after they have been stored (Krugman and Jenkinson 1974). Another not widely appreciated cultural benefit of cold-moist stratification is that early germination is slowed, creating an even flush of germination when the sown containers are placed in a warm propagation environment (Bonner and others 1994).

The traditional practice of mixing seeds with a moist medium is still used for some forest and conservation species. Some nurseries mix seeds with damp *Sphagnum* moss in a plastic bag and place it in a refrigerator (figure 6.2.22B/C). The condition of the seeds is checked weekly, and they are sown after the prescribed stratification period or planted as germinants (see section 6.2.8). Naked stratification involves soaking seeds in water to obtain full imbibition, draining off excess water, and placing the seeds in polyethylene bags in refrigerated storage where the temperature is held slightly above freezing. Running water rinses are preferred to standing soaks because the bubbling water keeps dissolved oxygen levels high and also cleanses the seedcoat of pathogenic organisms. In a study with Douglas-fir (Axelrood and others 1995), the percentage of seeds contaminated with the *Fusarium* fungus increased during stratification after a standing water soak; seedlots treated with running water imbibition showed significantly decreased levels of post-stratification contamination.

Successful stratification requires that four conditions be met:

Moisture and aeration-Operationally, these 2 factors must be considered together because they can be inversely related in the stratification environment. Effective stratification requires that seeds be fully imbibed and not allowed to dry out for the entire treatment period. The moisture contents at which full imbibition occurs varies among coniferous species although soaking seed in running water at room temperatures for 24 to 48 hours is usually adequate (Barnett 1981). If seeds are not fully imbibed, stratification will be less effective and will be reflected in slow or irregular germination. Seeds of some species are damaged by soaking for too long, however. For example, the viability of longleaf pine seeds is reduced by soaking for more than 8 hours (Barnett and Pesacreta 1993). After imbibition, seeds are drained and placed in polyethylene bags. The volume of seeds per stratification bag should be kept relatively small to ensure good aeration throughout, and the bags should be made of plastic no thicker than 0.102 mm (4 mil). This thickness of plastic allows some oxygen and carbon dioxide exchange- **remember that seeds are alive and "breathing"**! Some nurseries insert a small hollow tube or straw in the top of the bag to increase aeration (figure 6.2.22D). Placing the bags on wire mesh racks ensures air exchange under the bag, and some nurseries hang the stratification bags from hooks. It is also a good practice to have someone move and massage the bags weekly to move seeds in the interior to the outside and ensure that no anaerobic conditions exist. It is a good idea to check for mold development at this time also.

Temperature---The best temperature for cold-moist stratification is dependent on the species and ecotype but most trees and shrubs from colder climates need temperatures slightly above freezing. The optimum temperature range for most temperate zone species is 1 to 5 °C (34 to 41 °F). Growers should make certain that their refrigeration units are functioning properly and that temperature-monitoring equipment is accurate because freezing desiccates the seeds and stops the stratification process (Macdonald 1986).

Duration of treatment---The prescribed length of the cold-moist stratification treatment can vary from 4 to 20 weeks, depending on species, variety, and ecotype (table 6.2.13). Longer stratification periods erase the inherent differences within a seedlot and so improve the speed

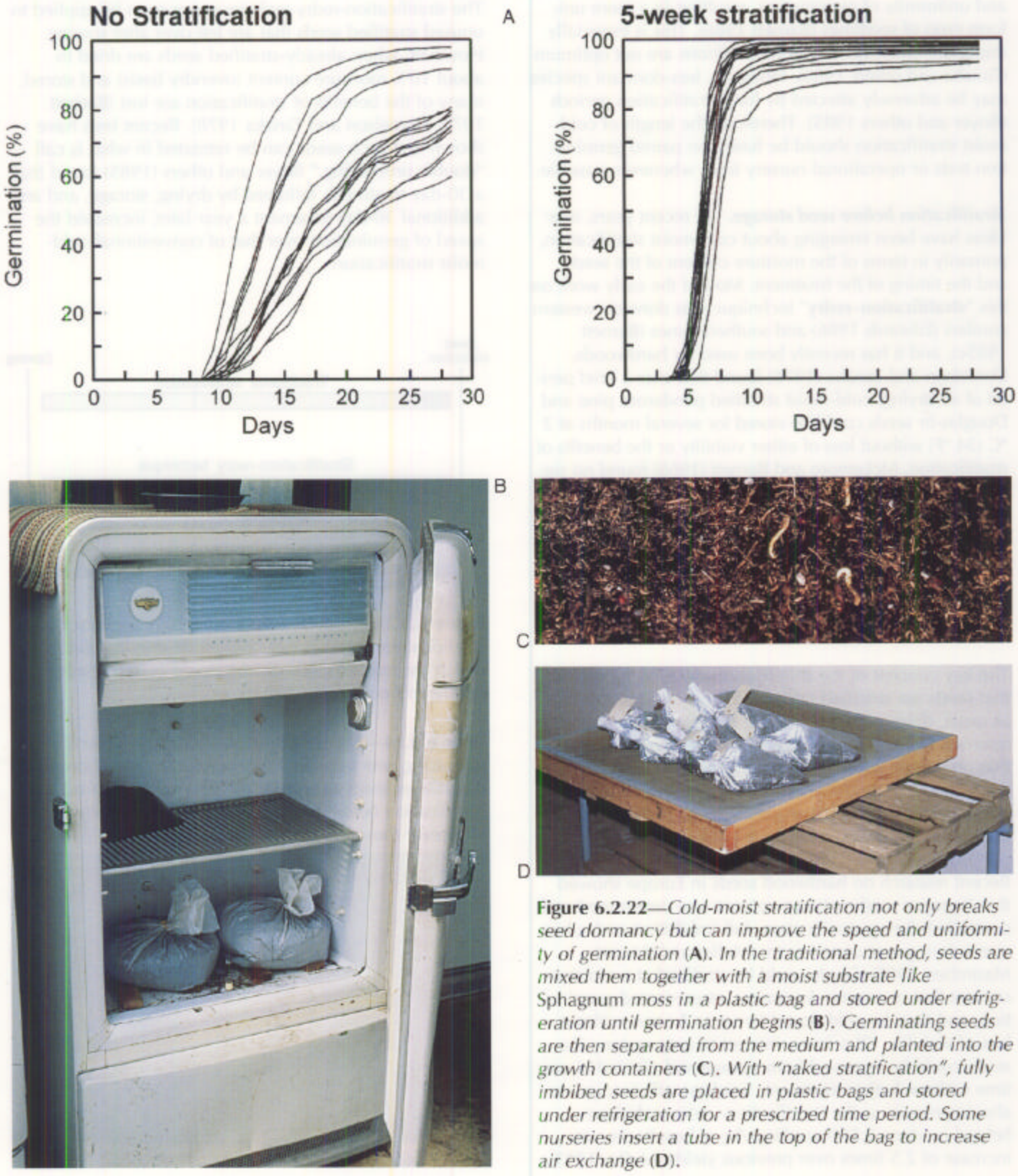


Figure 6.2.22—*Cold-moist stratification not only breaks seed dormancy but can improve the speed and uniformity of germination* (**A**). *In the traditional method, seeds are mixed them together with a moist substrate like* Sphagnum *moss in a plastic bag and stored under refrigeration until germination begins* (**B**). *Germinating seeds are then separated from the medium and planted into the growth containers* (**C**). *With "naked stratification", fully imbibed seeds are placed in plastic bags and stored under refrigeration for a prescribed time period. Some nurseries insert a tube in the top of the bag to increase air exchange* (**D**).

and uniformity of germination, resulting in a more uniform crop of seedlings (Barnett 1986). This is especially important when germination conditions are not optimum (Tanaka and others 1986). However, less-dormant species may be adversely affected by long stratification periods (Boyer and others 1985). Therefore, the length of cold-moist stratification should be based on paired germination tests or operational nursery trials whenever possible.

Stratification before seed storage. In recent years, new ideas have been emerging about cold-moist stratification, primarily in terms of the moisture content of the seeds and the timing of the treatment. Most of the early work on this "**stratification-redry**" technique was done on western conifers (Edwards 1986) and southern pines (Barnett 1985c), and it has recently been used for hardwoods. Danielson and Tanaka (1978) found that after a brief period of air-drying, cold-moist stratified ponderosa pine and Douglas-fir seeds could be stored for several months at 2 °C (34 °F) without loss of either viability or the benefits of stratification. McLemore and Barnett (1968) found no significant decrease in germinability using loblolly pine seeds that were treated and then stored for 1 year at different moisture contents and temperatures. Seeds stored at just above freezing temperatures and moisture contents greater than 25% but below full imbibition continued to increase in germinability. Edwards (1981) reported the same response with seeds of true firs.

The key concept of the stratification-redry technique is that seeds are stratified under cold and moist conditions as usual, then redried to a lower moisture content and returned to cold storage (figure 6.2.23). The benefits are that premature germination during stratification is largely prevented, and germination rates are improved to the point that total germination can even be higher than with traditional presowing treatments (table 6.2.14).

Recent research on hardwood seeds in Europe showed that if proper seed moisture content was determined and controlled during stratification, full imbibition and subsequent drying was unnecessary (Muller and Bonnet-Masimbert 1989). Seeds could be stratified at a moisture content that overcame dormancy yet prevented germination, and then be cold stored for up to 5 years without loss of viability. Of primary interest to propagators, the seeds could be removed from storage and planted at any time without further treatment. Seed-use efficiencies are also impressive as the stratification-redry technique helped produce 2,500 seedlings/kg of beechnuts-an increase of 2.5 times over previous yields (Muller 1993).

The stratification-redry technique can even be applied to unused stratified seeds that are left over after sowing. However, when already-stratified seeds are dried to about 10% moisture content (ovendry basis) and stored, many of the benefits of stratification are lost (Barnett 1972, Danielson and Tanaka 1978). Recent tests have shown that such seeds can be retreated in what is call "double prechilling." Boyer and others (1985) found that a 30-day treatment, followed by drying, storage, and an additional 30-day treatment a year later, increased the speed of germination over that of conventional cold-moist stratification.

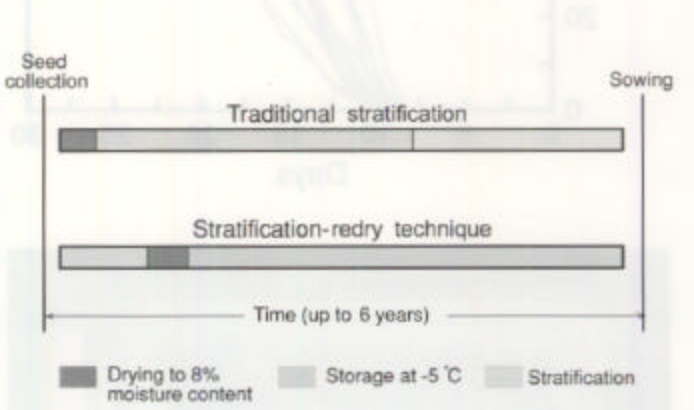


Figure 6.2.23—*The "stratification–redry" technique is a modification of traditional cold-moist stratification in which the treated seeds can be stored before sowing (modified from Muller 1993).*

Table 6.2.14—*The stratification–redry technique is a promising new treatment for overcoming seed dormancy that allows seeds to receive the benefits of cold-moist stratification before storage so that they are ready to sow whenever they are needed*

Seed lot # (European beech)	Storage duration (months)	Germination % of stratified seeds	
		Before storage	After storage
A	72	61	71
B	42	72	72
C	30	87	70
D	6	88	78
E	6	87	89
F	6	92	90
Mean	n/a	81	78

Source: Muller (1993).

6.2.5.5 Double or combined dormancy

The seeds of some forest and conservation species are particularly difficult to propagate because the dormancy level varies in the embryo or is due to a combination of factors (table 6.2.11).

Warm-moist stratification. There are two cultural objectives of this dormancy treatment: to soften a hard seedcoat, and to encourage the growth of an underdeveloped embryo. The former is hastened by increased microbial decomposition of the seed coat and the warmer temperatures simulate the over-summer period that occurs in nature (Macdonald 1986). With some species, like white oaks, the epicotyl goes through dormancy while the radicle does not, and so a warm-moist stratification treatment allows complete germination when the seeds are sown. Seeds of some other species germinate better when they are given a warm-moist period immediately before cold-moist stratification (table 6.2.13).

The requirements and procedures for the warm-moist stratification treatment are basically the same as for cold-moist stratification except that the temperatures are increased to 18 to 29 °C (65 to 85 °F). Seeds must be fully imbibed to benefit from warm-moist stratification and must be packaged and moved regularly to encourage good aeration. Warm-moist stratification usually takes between 4 to 12 weeks although this varies considerably between species. Some nurseries imbibe seeds and place them in plastic bags, just like they do before cold-moist stratification, and then hang them inside a warm greenhouse or place them on a heated floor or bench in a vegetative propagation structure (figure 6.2.24). If a larger volume of seeds must be processed, some nurseries have constructed an insulated room for warm .stratification with heat lamps to maintain temperatures at 24 to 27 °C (75 to 80 °F) (Macdonald 1986).

Combination treatments. Some seeds have a combined dormancy that consists of a hard seedcoat plus an embryo dormancy (table 6.2.13), and developing seed treatments for these species is especially challenging. For example, it is possible to overcome the hard seedcoat of eastern redbud with hot water or acid soaks, but the seeds will still not germinate due to their internal dormancy. A combination of either acid or mechanical scarification followed by a relatively short cold-moist stratification period was found to be effective (figure 6.2.25).

Challenging species. Lest the novice grower get the impression that overcoming dormancy is a routine cultural procedure, some species still cause problems including western white pine and Rocky Mountain juniper (figure 6.2.26A). Although much research has been devoted to achieving prompt and even germination

Figure 6.2.24—*Warm-moist stratification. One technique involves placing fully-imbibed seed in a heated greenhouse where the moisture content is kept high by a covering of wet burlap.*

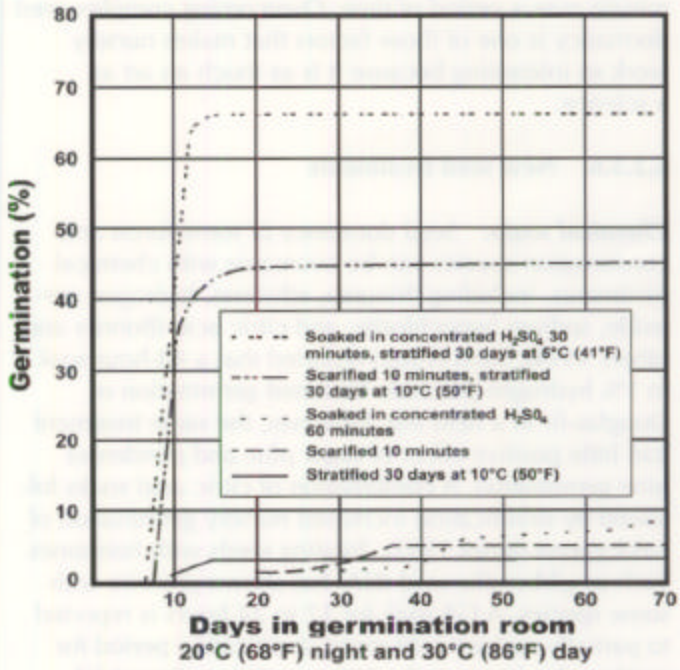


Figure 6.2.25—*Double dormancy in eastern redbud seeds requires both acid scarification and cold-moist stratification (from Bonner and others 1974).*

in the nursery for these problem species, more work still needs to be done. Part of the answer may be that the degree of dormancy varies from year to year or that some as-yet unknown chemical germination inhibitor is present.

In some cases, the answer might be to try and mimic nature. For example, Rocky Mountain juniper seed normally requires a warm-moist stratification followed by a period of cold temperatures (table 6.2.13), and a Colorado nursery has developed a "back-to-nature" technique to satisfy these requirements. During mid-summer, a mesh bag filled with juniper seeds is buried in soil at a depth of 10 cm (4 in.), irrigated, and allowed to naturally stratify until late winter. The bag is dug up the following February, when seeds are showing signs of germinating (figure 6.2.26B/C). They are then sown by hand in containers and grown under normal culture (Moench 1995). Seed germination of several tree species including maple, hawthorn, and basswood was improved by pre-treatment with a compost activator that chemically softens seedcoats, and thereby mimics the conditions of natural overwinter stratification (Cullum and Gordon 1994).

Nature has devised some intricate tricks to ensure the survival of the species by making certain seeds will germinate over a period of time. Overcoming complex seed dormancy is one of those factors that makes nursery work so interesting because it is as much an art as a science.

6.2.5.6 New seed treatments

Chemical soaks. Seed dormancy of some forest and conservation species can be overcome with chemical treatments, including thiourea, ethylene, hydrogen peroxide, sodium hypochlorite, and citric acid (Bonner and others 1994). Stein (1965) reported that a 48-hour soak in 1 %, hydrogen peroxide hastened germination of Douglas-fir in a field test. However, the same treatment had little positive effect of sugar pine and ponderosa pine germination. A combination of citric acid soaks followed by stratification increased nursery germination of baldcypress (Jones 1962). Treating seeds with hormones such as gibberellic acid (GA) has shown promise with some species. A GA soak for 12 to 24 hours is reported to partially replace cold-moist stratification period for northern bayberry, and a 100 ppm GA treatment followed by a 7-day cold stratification has shown promising results for sweetgum (Macdonald 1986). Treatment with plant hormones is a logical approach and we can only hope that more research will be forthcoming.

Figure 6.2.26—*Seed propagation of some forest and conservation species, such as Rocky Mountain juniper, continues to be a challenge because the morphological and physiological nature of their dormancy is poorly understood* (**A**). *However, imitating natural processes by burying bags of seeds in late summer and digging them up the following spring* (**B**) *overcomes the complex dormancy* (**C**).

Priming. Seed priming, or osmoconditioning, describes a presowing hydration process in which seeds are incubated at optimum temperatures but prevented from germinating until it is time for sowing. Primed seeds are commonly used for growing agricultural crops, and treated seeds can even be stored for several weeks (Kren 1994). Liquid priming uses osmotic solutions, particularly polyethylene glycol (PEG), whereas solid matrix priming involves a slurry of calcined clay and water. The main benefits of seed priming is that seedling germination and emergence is faster and more uniform. Simak (1976) found that an 11-day pretreatment of Scots pine at -800 kPa (-8 bars) with a PEG solution improved germination. However, Haridi (1985) and Fleming and Lister (1984) in similar experiments, found that results varied by species and seed sources. Consequently, priming has not become an accepted presowing treatment for forest tree species. Seeds provide a convenient delivery system for biocontrol agents, such as the beneficial fungi *Trichoderma* spp. and *Gliocladium* spp. or even mycorrhizal fungi, and so these treatments could be a promising new application of seed priming (Taylor and Harman 1990).

6.2.6 Presowing Treatments To Facilitate Seed Handling

Many seeds of forest and conservation species are small or irregularly shaped, making them difficult to handle during sowing. Seeds of some horticultural species are routinely treated with coatings or are pelletized to make seed sowing easier and more precise. "Coating" denotes the application of a substance to a seed that does not appreciably change its size or shape, whereas "pelletizing" or "pelleting" refers to the addition of inert fillers to increase the uniformity of seed size and weight (Taylor and Harman 1990).

6.2.6.1 Coating

Seeds can be coated with a thin layer of colored powder, making them easier to handle by increasing the uniformity of the seed coat surface. This is particularly important during mechanical sowing to assure the proper number of seeds per container cavity. Coatings can eliminate the static electricity on the seed coat of small seeds that can cause them to clump together and cling to other surfaces. Some nurseries use ordinary talc to coat seeds with a white color, but other organic dyes are also available. Yellow is popular because it is easy to see on the darker-colored growing medium (Kren 1994). Growers use coatings of different colors to allow quick identification of seeds of difference ecotypes or similar-sized species. Many other seed coatings including bioprotectants, fertilizers, and materials that help supply oxygen or retard imbibition of water have been used in horticulture (Taylor and Harman 1990).

6.2.6.2 Pelletizing

This involves enclosing small seeds within a thicker coating to make them larger and more uniform in size and weight. Seeds are tumbled in a drum with an inert filler and an adhesive until the desired increase in volume is obtained. After treatment, the pelletized seeds are dried and can be stored (Taylor and Harman 1990). Pelletizing makes small or irregularly shaped seeds easier to handle, especially during mechanical sowing. Larger and heavier pelletized seeds can be picked up better by automatic seeders and placed more precisely in the center of the container cavity (Kren 1994). Many of the commercial forest species, such as pines, have large uniform seeds and so pelletizing is not common in most forest and conservation nurseries. Seeds of Eucalyptus spp. are very small, however, and cannot be separated from the chaff during processing. A Swedish forestry firm has been able to clean the seeds of several eucalypts and pelletize single seeds into small, spherical pellets about 3 mm (0.11 in.) in diameter (figure 6.2.27A). In Italy, pelletized seeds of eucalypts have been direct-sown into containers for over 10 years, thereby overcoming the root deformation associated with transplanting (Piotto 1994). Seeds of western redcedar are small with wings on both sides and so are routinely pelletized prior to sowing in British Columbia container nurseries (figure 6.2.27B). Pelletized seed must not be allowed to dry out, and therefore proper irrigation is essential to ensure that the coating breaks down and germination occurs normally (Kolotelo 1996). The pelletizing process may hold promise for other forest and conservation species that are grown in sufficient number to make the process economical. As precision sowing becomes more common, pelletizing will become a more accepted practice.

Figure 6.2.27—*Pelletizing can make seeds easier to sow: very small seeds, such as these eucalyptus seeds* (**A, left** = *bulk seed from seed dealer;* **middle** = *recleaned seed;* **right** = *pelletized seed*), *or seeds with wings, such as western redcedar* (**B**, **left** = untreated; **right** = treated).

6.2.7 Seed Cleansing and Disinfection

Seeds of commercial conifers are normally contaminated with fungi and bacteria, but most of the microorganisms are considered saprophytic, with no adverse affects on seed germination or seedling development (Belcher and Waldrip 1972). With the advent of container culture, however, it became apparent that seedborne pathogens can be an important cause of nursery disease. A number of different pathogenic fungi have been isolated from conifer seedcoats (figure 6.2.28A), and pathogens can also be carried internally (Littke 1990). For example, 8 to 20% of the seeds from 5 longleaf pine seedlots were found to be infested with 5 different species of the *Fusarium* fungus, and all were shown to be pathogenic (Pawuk 1978). All 12 Douglas-fir seedlots assayed for *Fusarium* in a recent British Columbia study were found to be infected, although the level of infection and the virulence of the *Fusarium* species varied considerably (Axelrood and others 1995). This variability makes it difficult to predict which species or seedlots of seeds will be affected.

The most common symptom of seedborne disease is slow and variable seed germination and seedling emergence. Unfortunately, these symptoms are usually attributed to poor-quality seed. Even if seeds germinate and seedlings emerge normally, seedborne fungi can cause post-emergence damping-off or cotyledon blight (figure 6.2.28B). Sometimes, the symptoms of a seedborne disease problem do not become evident until root rot shows up later in the season. (A complete discussion of seedborne disease identification and control can be found in volume five of this series.)

Historically, nursery managers treated all their seeds with fungicides before sowing. However, pesticide use has come under increasing scrutiny because of phytotoxicity to germinating seeds as well as newer concerns about worker safety and environmental pollution. The following steps are recommended for managing seed diseases (Campbell and Landis 1990):

1. Determine if a seedborne disease problem exists by carefully observing germination and monitoring seed use efficiency
2. If a problem is suspected, conduct seed assays to identify the specific pathogens involved
3. Treat seedlots that are shown to be contaminated

It is a good idea to go ahead and assume that seeds do carry pathogens and institute cultural practices that prevent potential pathogens from entering the normally sanitary container nursery environment. However, if growers want to confirm that they have a seedborne disease problem, then a sample of seeds can be assayed for pathogens. Some seed testing laboratories offer a phytosanitary test (figure 6.2.12), or a sample can be sent to a nursery pathology lab. An enzyme-linked immunosorbent assay (ELISA) test has been developed to confirm the fungal pathogens *Sirococcus strobilinus* and *Caloscypha fulgens* on spruce seed (Littke 1990). Once a specific fungi is confirmed, then one of the following treatments, which are listed in order of increasing toxicity, can be instituted.

6.2.7.1 Aerated water rinse

As already discussed in section 6.2.5, soaking seeds in an aerated rinse is a standard procedure for preparing nondormant seeds for sowing or as a treatment prior to stratification. It has also been shown to be an effective way to control nursery diseases and reduce the use of toxic pesticides (Dumroese and others 1990). Cleansing conifer seeds under running water for 48 hours was effective in reducing *Fusarium* levels and this simple treatment also will wash away other pathogens on the seedcoat. Seeds should be poured into a nylon mesh bag with enough room to allow them to move, and the bag placed in a tank of water. Inserting a irrigation hose will generate enough water pressure to gently agitate the seeds and wash contaminants out with the water running over the top of the tank. Some nurseries have used modified hot tubs to treat large volumes of seed before stratification.

6.2.7.2 Chemical sterilants

Hydrogen peroxide (H_2O_2) has been used to sterilize seeds for many years, although the concentration and treatment time are critical (figure 6.2.28C/D). A 40-minute soak in 30% H_2O_2 (laboratory grade) virtually eliminated all seedborne organisms on Douglas-fir seeds, and also was effective on southern pines with treatment times ranging from 15 minutes to 1 hour (Barnett 1976). The common antiseptic grade of H_2O_2 is only 3% and much less caustic than the laboratory-grade chemical. Recent operational trials found that a 4-hour treatment with 3% H_2O_2 was very effective in reducing levels of seedborne Fusarium on coastal Douglas-fir and western larch seeds. Subalpine fir was more sensitive, however, so a 1-hour treatment gave the best control with the least chance of phytotoxicity (Neumann and others 1997).

In addition to effectively sterilizing seed coats, H_2O_2 increases germination of some pine seeds. Germination of some longleaf pine seedlots, especially those with low viability, can be increased by a 30- to 60-minute soak in H_2O_2 (Campbell 1982). The North Carolina Claridge State Nursery operationally soaks their longleaf pine seeds in 30% H_2O_2 to reduce fungal contamination and improve germination and found that this treatment increases seedling stocking by about 10% after 90 days. Lots of 9 to 11 kg (20 to 25 lbs) of seed are placed in porous nylon mesh bags and soaked for 55 minutes in the H_2O_2 solution at 24 °C (75 °F). Then, the bags are

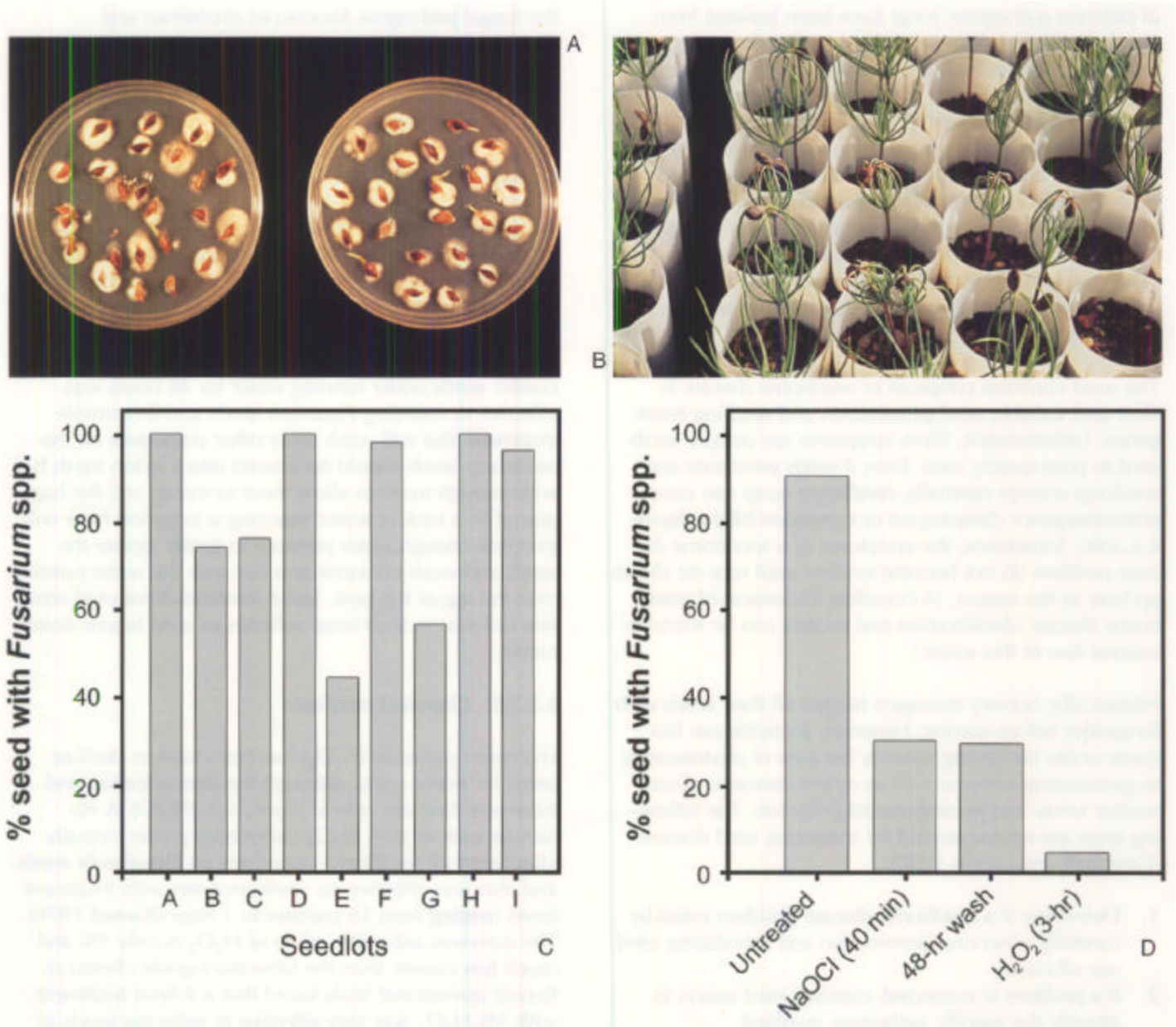


Figure 6.2.28—*Many seeds are contaminated with fungi and bacteria* (**A**)*, some of which are pathogenic and can cause diseases including damping-off and cotyledon blight* (**B**)*. Seedlots of eastern white pine were found to be highly infested with the pathogenic fungus* Fusarium *spp.* (**C, left**)*. Although bleach (NaOCl) and a running water rinse removed much of the inoculum, hydrogen peroxide (H_2O_2) was the most effective* (**D, right**) *(A, courtesy of A. Kanaskie, Oregon Department of Forestry; C & D, modified from Buschena and others 1995).*

drained and thoroughly rinsed in 3 separate containers of clean water and allowed to surface-dry (Barnett and McGilvray 1997).

Chlorine bleach (sodium hypochlorite) also has been used on seeds as a surface sterilant. Operational nursery use of solution of 2 parts common household bleach (5.25% sodium hypochlorite) to 3 parts water indicate that it is a less-reliable seed treatment than hydrogen peroxide, but it is safer to use (Wenny and Dumroese 1987). The other advantage to household bleach is that it is inexpensive and widely available.

6.2.7.3 Hot water

Hot water soaks are a traditional seed sterilization technique for horticultural seeds and also would be effective on those of forest and conservation species. Seeds are placed in nylon mesh bags, immersed in a tank of warm water--49 to 57 °C (120 to 135 °F)-for 15 to 30 minutes, and then cooled in running tap water (Handreck and Black 1994). Aerated steam is an even safer way to apply heat because it does not leach the seeds. Seeds are spread on a mesh screen in an insulated chamber connected to an aerated steamer so that the steam is dry when it reaches the chamber. Temperatures reach the same range as the hot-water method and the treatment lasts 30 minutes, but treatments as short as 10 to 15 minutes also may be effective. At the end of the treatment, temperatures must be lowered rapidly by a cold-water rinse and the seeds allowed to dry (Hartmann and others 1997).

Although the best temperature/time treatment depends on the pathogen to be controlled and would have to be determined for different species, hot water or steam is a safe, simple and environmentally friendly way to cleanse seeds.

6.2.7.4 Pesticides

Historically, fungicides were routinely applied to seeds to control diseases, especially damping-off. In 1981, captan, thiram, and benomyl were listed as seed fungicides for the control of the Fusarium fungus (Bloomberg 1981); however, the number of pesticides registered for nursery use continues to be reduced every year. In container nurseries, the possibility of phytotoxicity from seed pesticides is more serious because the biological and chemical buffering capacity of artificial growing media is very low (Sutherland and Van Eerden 1980). Therefore, use of fungicidal seed treatments must be justified by the identification of a specific pathogen and operational nursery trials to show that these treatments are truly effective.

The use of protective repellent coatings to limit bird depredation is not needed in fully enclosed propagation structures. However, more container seedlings are being grown in open compounds and so it is necessary to protect seeds from birds. The use of repellent coatings including thiram or anthraquinone is common in bareroot nurseries in the South. Anthraquinone with a latex sticker is safer to handle and has less effect on germination, but its powder formulation makes it troublesome to apply. Only label rates of anthraquinone or thiram should be used, because heavier rates may slow germination (May 1985). Again, nurseries should confirm that bird-repellent coatings are safe and effective before initiating full-scale use.

6.2.8 Seed Sowing

The actual process of sowing seeds into containers varies with the type of seed and seed quality as determined by a viability test. Large or irregularly shaped seeds must be sown by hand, whereas small seeds of uniform shape can be mechanically sown. One seed can be sown per container for high-quality seedlots such as those from seed orchards, but 2 to 6 seeds per container are used for seedlots with lower germination percentages. **Only the highest quality seeds should be used in container nurseries, however, because there are cultural and economic drawbacks to multiple seed sowing.** Some nurseries have seed quality standards and will not accept seedlots with germination tests below a certain minimum. When several seedlings emerge in the same container they compete for light, water, and nutrients, resulting in initial growth rates that are lower until the seedlings are thinned to 1 per container. Thinning costs are higher with multiple sowing and there is always the possibility of damaging the crop seedling when the others are removed.

Three different sowing techniques have been used in forest and conservation nurseries: direct seeding, planting germinants, and transplanting emergents (table 6.2.15).

6.2.8.1 Direct seeding

Direct seeding is defined as the placement of seeds directly into the growth container when they are ready to germinate and grow (table 6.2.15). If seeds are dormant, then they must be treated before the planned sowing date. By far the majority of seeds of commercial tree species such as pines are direct-sown, but the situation is different for other forest and conservation species because most have seeds with irregular shapes and difficult dormancy requirements. In a native plant nursery in the Intermountain West, only 10% of the species were direct-seeded (Landis and Simonich 1984).

The seedling operation begins with the calculation of the sowing rate based on the results of germination tests-as tempered by the grower's past experience.

Determining sowing rate per container. For a container nursery to reach maximum production efficiency, empty cavities must be avoided. Unfortunately, seeds of most forest and conservation species will rarely have germination percentages higher than 90%. Orchard seed of commercial conifers is the exception, with the germination percentage of some seed lots approaching 100% and therefore these highly valuable seeds are sown 1 seed per container. For most species, however, growers sow several seeds per cavity to make sure that they have no empty containers. Growers use several strategies to achieve maximum container occupancy when direct seeding:

- Sow 1 seed per cavity but sow some extra containers **(oversowing)**
- Single-sow and transplant emergents from additional seed trays
- Multiple-sow and thin to 1 emergent per container

The decision will depend on seed availability and cost, germination test results, container type, labor costs, and available growing space. If the grower has extra space and uses containers with removable cells that can be consolidated, then the oversowing option works well if the sowing of another species can be delayed for a month or so. The second option of single-sowing with subsequent transplanting of emergents that are grown in separate seed trays is viable if labor costs are not prohibitive. (See section 6.2.8.3 for more information on transplanting emergents.)

Most nurseries sow multiple seeds per container and then thin down to 1 seedling after germination is complete. The decision of how many seeds to sow can be calculated directly or determined from tables that use sowing rates and expected germination to predict the number of vacant and stocked cavities (Balmer and Space 1976). A complete set of sowing probability tables can be found in Tinus and McDonald (1979).

The direct calculations are relatively simple, however, and most growers should be able to compute the proper sowing density with little effort. The technique is based on the concept of binomial probability-a seed either grows or it does not. If "X" equals the probability of a seed germinating and "Y" equals the probability of its failing to germinate, a binomial expansion can be constructed that includes all possible occurrences. The following example shows the possibilities when 2 seeds are sown per container (Schwartz 1993):

$$(X+Y)^2 = X^2 + 2XY + Y^2$$

where: X^2 = the probability of both seeds germinating
$2XY$ = the probability of only one seed germinating
Y^2 = the probability of neither seed gernlinating

Table 6.2.15—*Characteristics of the four main seed propagation methods for forest and conservation species*

Propagation method	Best method for:	Advantages	Disadvantages
Direct seeding: Seeds are sown into growth containers with or without pretreatment	* Seeds of medium to large size * Uniformly-shaped seeds with smooth seedcoats * Seeds of high quality with viability test information	* Quick * Minimizes seed handling * Mechanical seeding possible * Less labor required * Sowing occurs all at once	* Requires seeds of known high quality * Dormant seeds must be pre-treated * Requires thinning and/or consolidation for difficult-to-germinate seeds * Inefficient use of growing space
Planting germinants: Pregerminated seeds are sown from stratification trays or bags into growth containers ("sowing sprouts")	* Very large or irregularly shaped seeds * Seeds of unknown quality or low purity * Valuable or scarce seedlots * Seeds requiring cold-moist or warm-moist stratification	* Good growing space utilization * Efficient use of seeds * Can adjust for unknown seed quality	* Slower and more labor intensive * Sowing can take weeks or months to complete * Crop development will not be uniform due to staggered sowings * Sowing date depends on stratification requirements * Root deformation possible if not done correctly
Transplanting emergents: Seeds are sown into seed trays to germinate; after a few weeks, seedlings are transplanted into growth containers ("pricking out")	* Small or fragile seeds * Seeds of unknown quality or low purity * Valuable or scarce seedlots	* Good growing space utilization * Efficient use of seeds * Can adjust for unknown seed * More uniform crop development	* Transplanting requires skill and is labor intensive * Difficult to control density in seed trays so disease potential is high * Root deformation probable if not done correctly
Miniplug transplants: Seeds are direct-sown into small containers and then transplanted to larger ones	* Seeds of small to medium size * Seeds of high quality with viability test information	* Good growing space utilization with resultant cost savings * Mechanical seeding and transplanting possible * Uniform crop development * No transplanting injury to roots	* Requires two sets of containers * Timing of transplanting is critical to avoid binding in miniplugs * Transplanting is labor-intensive and therefore costly

Source: Modified from Landis and Simonich (1984).

As long as germination test data are known, the proper number of seeds to sow per container can be easily determined by entering the "germination failure" on a hand-held calculator with a universal power key (YX). The procedure consists of keying-in the decimal equivalent of the germination failure, pushing the universal power key, entering the number of seeds you might sow, and finally pushing the "equals" key. If your calculator does not have a universal power key, then just use repeated multiplication. For example, a seedlot with 78% germination has a 22% failure score:

For 1 seed per cell: $(0.22)^1 = 0.2200 = 22\%$ empty cells
For 2 seeds per cell: $(0.22)^2 = 0.0484 = 4.8\%$ empty cells
For 3 seeds per cell: $(0.22)^3 = 0.0106 = 1.1\%$ empty cells
For 4 seeds per cell: $(0.22)^4 = 0.0023 = 0.2\%$ empty cells

Thus, the calculation becomes a "law of diminishing returns" and the best number of seeds to sow will depend on seed availability, seed cost, cost of thinning, and the reliability of the germination test. In this example, most nurseries would be satisfied with sowing 3 seeds per cell.

Many nurseries have "Seed Use Forms" that show the necessary information for each seedlot. Not only are these invaluable for internal record keeping but are a good way to show customers how the seed requirement is calculated for each order (table 6.2.16).

Hand-sowing. Small seedlots are always sown by hand because it takes a certain minimum amount of seeds to operate a seeder. At the present time, there are no seeders available that can handle large seeds (figure 6.2.29A), and so they also must be hand-sown. Very small seeds are also difficult to handle, not only because of their size but also because static electricity makes them clump together. However, they can be sown with a wet tooth pick or metal pin (figure 6.2.29B-G).

Seeding equipment. Seeds of uniform shape and with a smooth seedcoat, such as pines, can be mechanically sown. Sowing equipment ranges from relatively inexpensive shutterboxes and homemade plate vacuum seeders (figure 6.2.29H) to commercial needle-point vacuum seeders that can deposit 1 seed per container with a high rate of accuracy. In mechanized nurseries, the seeder is included in a sowing line where containers are filled with growing medium, sown, and covered in one operation. However, the precision of many seeders is such that workers still have to fill empty containers by hand (figure 6.2.29I). (See section 1.4.5.3 in volume one of this series for a complete discussion on seeding equipment.)

Table 6.2.16—*Typical seed use form for calculating the seed requirements for container nursery crops*

Nursery name:_____
Date:_____
Address:_____
Contact person:_____
Method of shipment:_____

Desired seed treatment:
None ☐
Cold moist stratification ☐
Other (specify) ☐ _____

Seedlot:_____
No. of seeds/weight (kg or lb):_____
Germination test (%):
No. of cavities to be sown*:_____
No. of seeds per cavity**:_____
Weight of seeds needed (kg or lb)***:_____
Date seeds will be needed:_____

* Total cavities, including oversowing:
1. Cavities to be sown × no. of seeds/cavity = total seeds to be sown
2. Total seeds to be sown ÷ no. of seeds/weight = weight of seeds needed

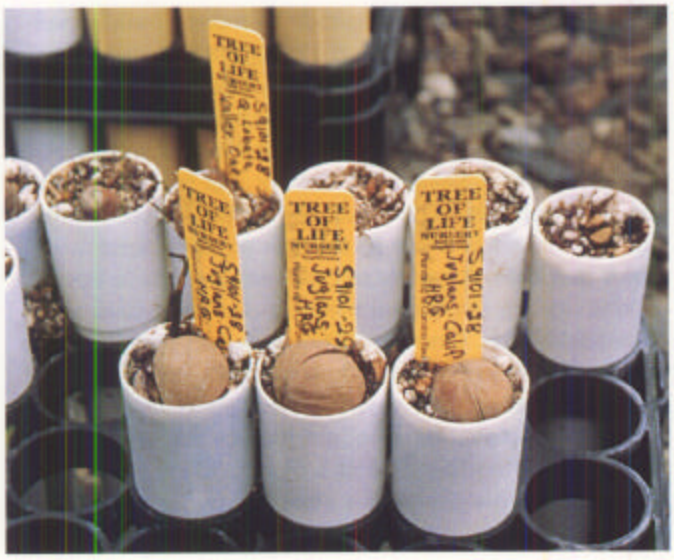
** Use these recommended sowing rates:

Germination (%)	Seeds/cavity
85–100	2
75–85	3
<75	**Not recommended**

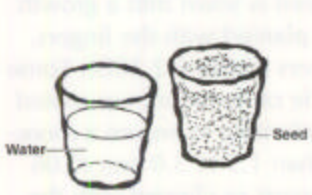
*** Round up to the nearest 0.1 kg. or 0.25 lb.

Source: Wood (1994).

The success of direct seeding depends on the accuracy of seed test information, the sowing technique, and conditions in the propagation environment. Novice growers must realize that actual seedling emergence may be different from the results of laboratory germination tests which are conducted under ideal environmental conditions. Therefore, nursery managers must adjust for this discrepancy based on their own operational experience.



A



B

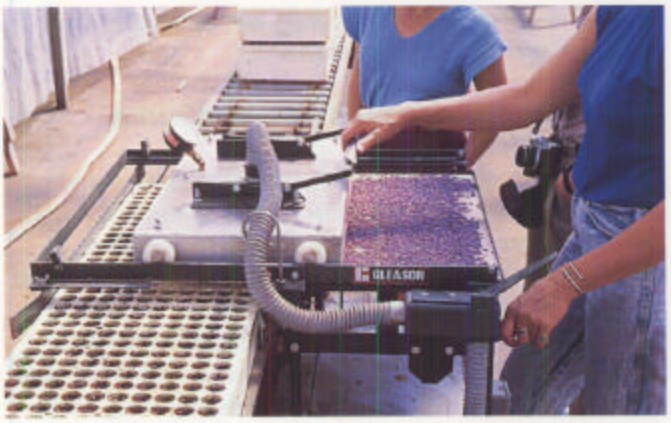
C

D

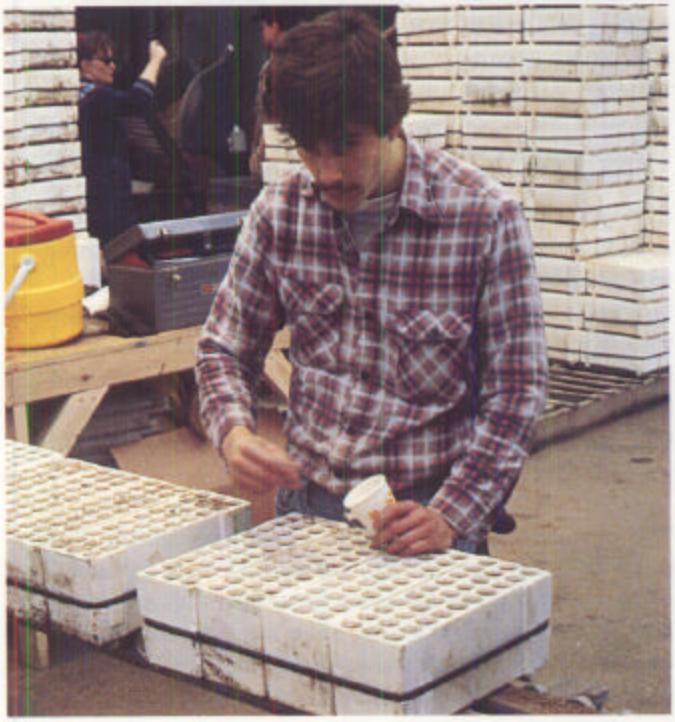
E

F

G



H



I

Figure 6.2.29— *For direct seeding, large seeds, such as these from the California walnut, can be hand-sown* (**A**), *but very small seeds are difficult to handle—such as these from shining gum—and can be sown with a moistened toothpick or metal pin* (**B**). *Wet the tip of the toothpick* (**C**), *and dip in into the dry seed* (**D**). *The seed adheres to the tip* (**E**) *and so can be sown into the container* (**F**) *where the multiple emergents are thinned to 1 seedling* (**G**). *Seeds of most commercial tree species can be sown with homemade or commercial seeding equipment* (**H**), *but many commonly used seeders lack precision and must be followed by workers who hand seed any empty cells* (**I**). *(B-G, modified from Weber and Stoney 1986.)*

Again, the importance of accurate and detailed record-keeping cannot be overemphasized.

6.2.8.2 Planting germinants from stratification

Germinant sowing consists of placing pregerminated seed into the growth containers, and is particularly well-suited for large seeds (table 6.2.15). This procedure is sometimes referred to as planting "sprouts" (Finnerty and Hutton 1993) but we feel that "germinants" is a more accurate and descriptive term. Planting germinants is most commonly used for seeds requiring cold-moist stratification but can also be used for seeds requiring warm-moist stratification. It can even be used for seeds of maples or junipers that require both treatments. Germinant sowing is particularly useful for seedlots of variable quality or for those for which no germination test data are available. It is commonly used for commercial conifers like true firs that typically have low germination tests and for large hardwood seeds like those of the oaks (figure 6.2.24). In an Intermountain West nursery specializing in native plants, the germinant technique was used for about 15% of the species (Landis and Simonich 1984). It is also popular in developing countries that do not routinely test their seed and where labor costs are low. Germinant sowing not only ensures that a live seed is placed in every container but that the resultant seedlings are larger because they can begin to grow immediately (table 6.2.17).

The germinant sowing process is relatively simple. Fresh seeds or seeds from storage are soaked in an aerated water tank for 24 to 48 hours to achieve full imbibition and cleanse their seedcoats. They are then either placed in either cold-moist or warm-moist stratification until they begin to germinate. Some propagators coat their seeds with a protective fungicide to reduce mold development (Finnerty and Hutton 1993), but this should only be done when absolutely necessary because of possible phytotoxicity and health concerns. Larger seeds are sometimes placed in plastic bags and mixed with a moist medium such as *Sphagnum* moss or wet burlap to maintain high humidity (figure 6.2.30 A). Smaller seeds are stratified naked in a tray so that germinating seeds are easier to locate. A variety of common trays have been used including stryrofoam meat trays or cake pans with clear plastic lids. One innovation involves spreading the seed in the fold of a mesh cloth between layers of moist peat moss-vermiculite growing medium (figure 6.2.30B). For cold-moist stratification, the bags or trays are placed under normal refrigeration at 1 to 2 °C (34 to 36 °F) or left under a moist cover in a greenhouse for warm-moist stratification.

The seeds are checked every few days or weeks to monitor germination, and as soon as the radicle begins to emerge (figure 6.2.30C), that seed is sown into a growth container. Larger seeds can be planted with the fingers, but smaller ones require tweezers (figure 6.2.30D). Some growers like to prune the radicle of dominant tap-rooted species, such as oaks, prior to planting to ensure a more-fibrous root system. No more than 1 .5 to 3.0 mm (0.06 to 0.12 in.) is trimmed with scissors or clipped with the thumbnail (Emery 1988). **The placement of the germinating seeds is very important.** The seeds must either be sown on their sides or with the radicle extending downward. Poorly placed seeds will develop a crook in their stems (figure 6.2.30E) that will become brittle and break when they become larger (figure 6.2.30F). The major disadvantage of the germinant technique is that sowing will be extended over several weeks or even months, depending on the degree of seed dormancy, and the resultant crop development will be uneven, producing seedlings with a wide range of sizes and ages (table 6.2.15).

Table 6.2.17—*Sowing germinated seed of hardwickia not only significantly increased seedling survival but also subsequent growth compared to soaked or untreated seed*

Seed treatment	Survival (%)	Height (cm)	Stem diameter (mm)
Untreated	63	7.8	0.8
Water soak	84	12.4	1.3
Pre-germinated	90	15.9	1.6

Source: Suresh and others (1994).

6.2.8.3 Transplanting emergents from seed trays or "pricking out"

Because many seeds of forest and conservation species are too small or fragile to be direct-seeded or even planted as germinants, another technique consists of sowing seeds into shallow trays. After germination, the emerging seedlings (**emergents**) are transplanted into growth containers (table 6.2.15). This procedure is also commonly-known as "pricking out" or "spotting off" (Emery 1988). Transplanting emergents is particularly

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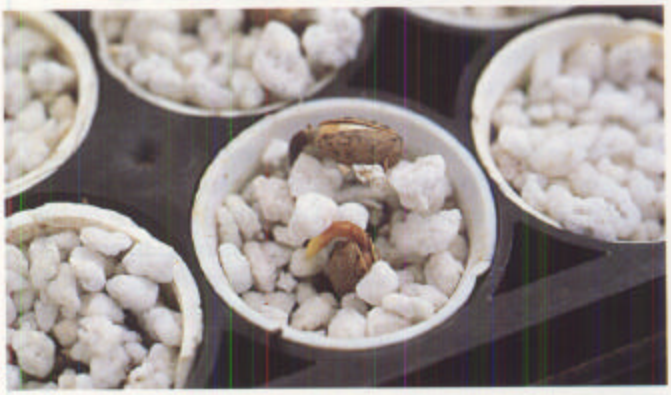

E

F

Figure 6.2.30—*For planting germinants, seeds are pretreated with cold-moist naked stratification* (**A**) *or in a medium* (**B**) *until they begin to germinate* (**C**)*; then the single germinants are hand-sown into the growth containers* (**D**)*. Germinating seeds should be properly oriented with the root pointed downward* (**E**) *or the seedlings will develop crooked stems* (**F**).

popular for native species because of their complex dormancy requirements and small or irregularly shaped seeds (Finnerty and Hutton 1993). In one native plant nursery, about 65% of the species were propagated by transplanting emergents (Landis and Simonich 1984).

Seeds requiring scarification must be treated before sowing, and those that require cold-moist stratification can be sown in trays in the fall and then placed in a refrigerator or even outside in a sheltered location to undergo natural stratification. In the latter case, the seed trays must be irrigated periodically to prevent desiccation and protected against rodent predation. When such trays are brought into the greenhouse in the spring, the seeds germinate almost immediately. Some species may germinate better at lower temperatures. For example, seeds of wintergreen are sown in seed flats in cold frames where the temperature is around 13 °C (55 °F) (Date 1994).

Transplanting emergents begins with sowing seeds in the germination trays. These shallow trays are filled with about 5 cm (2 in.) of standard peat moss-vermiculite growing medium that is lightly tamped until it is firm, but not compacted. Larger seeds are scattered over the surface of the medium by hand, or smaller seeds can be sown with a salt shaker with the holes in the top enlarged. The sown seeds are covered with a light application of a fine-textured mulch such as sand-blasting grit, irrigated, placed into a greenhouse and misted lightly (figure 6.2.31A). When the germinating seedlings reach the cotyledon stage and begin to grow their first set of primary leaves, they are ready for transplanting to the growth containers (figure 6.2.31 B). The best size or age for transplanting varies by species, however. Broadleaf species with large cotyledons, such as sumacs, should be transplanted at the 2-leaf stage whereas those with smaller cotyledons, such as monkeyflower, should not be transplanted until the 6- or 8-leaf stage (Emery 1988). With black spruce and jack pine, transplanting was impracticable after primary needles have developed, as the incidence and severity of root deformity increased with the amount of time past the erect hypocotyl stage (Scarratt 1991).

Transplanting consists of working the emergents loose from the seed tray (figure 6.2.31 C), making a dibble hole in the growing medium in the growth container, placing a plant in the hole, and firming the medium around the stem (figure 6.2.31 D). Unfortunately, this procedure sometimes produces a "J-root" or kink in the seedling stem (Gordon and Hayes 1994). This deformity can not only reduce growth in the nursery but also causes mechanical weakness or mortality after outplanting (figure 6.2.31 E). Reducing the length of the primary root of spruce seedlings by 50% was found to greatly improve transplanting success, but this clipping treatment was less effective as the emergents grew larger (McCure 1995; Singh and others 1984). In another innovative way to overcome root kinking, growers have developed an transplanting tool consisting of a sharpened probe with a V-notch in the tip (figure 6.2.31 F). The top of the emergent is held with one hand and the bottom of the root is hooked with the notched tip of the transplanting tool (figure 6.2.31 G). The root is pushed down into the soil or growing medium until the seedling is at the proper depth. Then, while still stabilizing the seedling, the hooked bottom of the root is cut off and the tool removed (figure 6.2.31 H). This simple technique leaves the emergent transplanted without the possibility of a "J-root" or other deformation so that roots can develop normally (figure 6.2.31 I).

Transplanting emergents requires some degree of skill but can be easily mastered with some simple training (table 6.2.15). The procedure is also labor intensive, compared to direct seeding or sowing germinants, but an experienced worker can transplant up to 2,000 emergents in an 8-hour day (Landis and Simonich 1984).

6.2.8.4 New sowing techniques

Nursery managers are constantly searching for better and more-cost-effective ways of sowing seeds.

Miniplug transplants. A relatively new seed propagation option is to direct sow the seeds in small volume containers ("miniplugs") or peat pellets. Once the seedlings have become established in these smaller cells, they can be removed and transplanted into the growth container. Transplanting is usually done by hand, and growers have developed innovative tools, such as dibbles and spatulas to make the procedures easier and faster (figure 6.2.32A). The stage of seedling development at the time of transplanting is very important because they must have a firm enough root plug to withstand handling but not so many roots that they will become deformed after transplanting (figure 6.2.32B).

Miniplugs have been successfully used for bareroot transplants for several years (Gelinas 1990), but this procedure is still very new in containers. This technology has particular application for nurseries growing large con-

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B

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D

F

E

G

H

I

Figure 6.2.31—*For transplanting emergents, seeds are hand-sown on top of growing medium in shallow trays and covered with a thin mulch* (**A**) *and then placed in a conducive environment where they germinate. When the emergents develop to the primary leaf stage* (**B**)*, they are carefully removed from the seed tray* (**C**) *and transplanted into the growth container* (**D**)*. Proper transplanting technique is critical or the seedlings will develop with crooked tap roots* (**E**)*. This defect can be avoided by using a sharp probe* (**F**) *to hook the base of the root* (**G**)*. While holding the stem, the root of the emergent is pushed down into growing media and the hooked tip cut off with a sharp downward motion* (**H**)*. This technique orients the seedling in a vertical position and the root pruning produces a more fibrous root system* (**I**)*.*

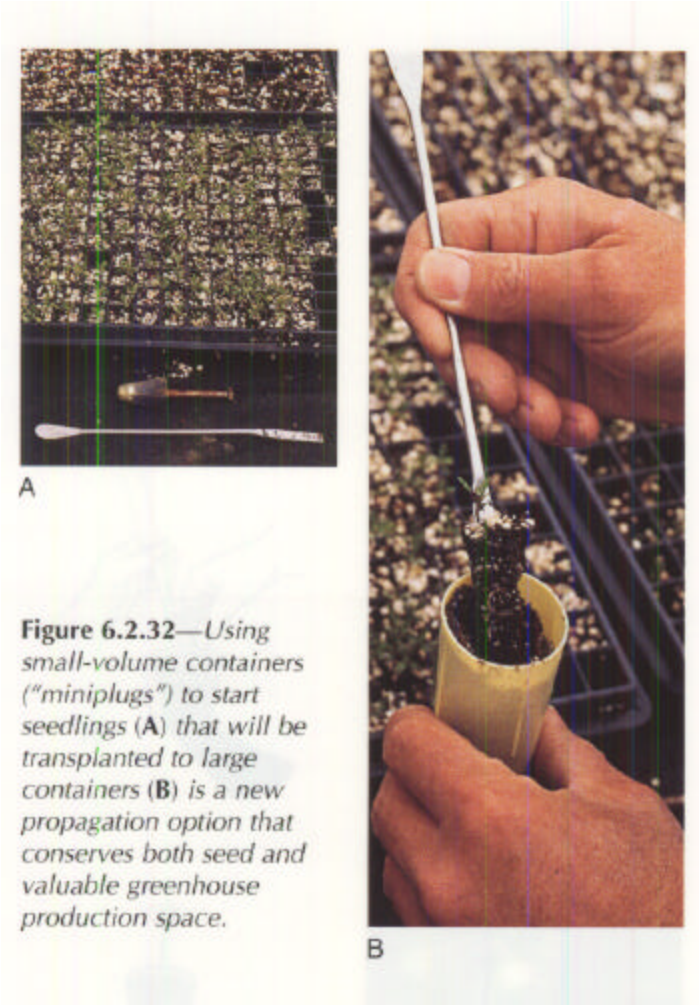

Figure 6.2.32—*Using small-volume containers ("miniplugs") to start seedlings (**A**) that will be transplanted to large containers (**B**) is a new propagation option that conserves both seed and valuable greenhouse production space.*

tainer stock because valuable growing space can be conserved by growing the miniplugs in a greenhouse. Once they are transplanted, they can be moved to shadehouses or open growing compounds which are much less expensive to operate. The biggest drawback to this technique is the cost of handling and transplanting (table 6.2.15). The savings of greenhouse space and heating must compensate for the cost of the additional containers and transplanting. Plug transplanting equipment has been used for flower and vegetable plugs for many years and miniplug transplanters are now available for forest and conservation seedlings. (See section 1 .4.5.6 in volume one of this series for more information.)

Fluid drilling. The technique of fluid drilling, which is also known as gel seeding, involves germinating seeds in aerated water at the optimum temperatures for germination until radicles emerge. Non-viable and slow-to-germinate seeds are removed from germinating seeds with density separation. The germinating seeds are mixed with a viscous gel and sown with specialized seeders (Taylor and Harman 1990). Fluid drilling maintains good moisture around the seeds and also protects them from rough candling. Another advantage is that gels can be used to deliver biocontrol agents such as fungicides to control seedling diseases such as damping-off.

In South Africa, seeds of eucalypts and pines with less Khan 90% germination have been operationally sown with gel seeding since 1986 (South and Young 1994). reeds of the same size and mass are germinated in water and then separated using a sugar solution. After separation, the germinants are sown with special precision vacuum seeders. Gel seeding is still experimental in the United States but has promise for high-value seeds. Barnett (1985b) showed that if high-quality southern pine seedlots (90% or greater germination) are prechilled for "I[--)out 60 days and then soaked in aerated water at 24 °C 75 °F), about 85% of the seeds will have their radicles emerge within 4 to 5 days.

Single-seed sowing. The number of seeds to sow per ~ ell is typically computed based on germination percentage as discussed in section 6.2.8.1. However, with seeds that are valuable or of limited availability, the economics of single-seed sowing are becoming more attractive. Increased labor costs for thinning also are a consideration: South and Young (1994) calculated that thinning costs were 34% greater for sowing 2 seeds/cell compared to the costs of single-seed sowing.

Single-seed sowing also has genetic benefits because of the unequal selection pressures posed by certain container nursery practices. It has been estimated that germination, thinning, and culling contribute 66, 20, and 14% respectively to the total variation in the final crop (ElKassaby and Thomson 1996). The authors recommend single-seed sowing as one way to maintain natural biodiversity in wild seedlots or to assume reasonable gain with genetically improved seed.

6.2.9 Seed Coverings

After seeds are sown into the container or cavity, they must be covered or "mulched" with a material that will keep them moist and protected until they can germinate. Seed coverings help hold the seed in contact with the growing medium and also reduce development of cryptogams such as moss, algae, and liverworts (figure 6.2.33A). (See section 5.1.5.4 in volume five of this series for more information on managing these pests.)

6.2.9.1 Types of coverings

Many materials have been used to cover seeds including standard growing medium components-shredded peat moss, vermiculite, and perlite. Organic materials work reasonably well although they encourage the growth of cryptogams in the moist environment necessary to germinate seeds (Tinus and McDonald 1979). Therefore, other inorganic materials such as coarse sand or granite grit have become more popular in recent years. Some materials are unpleasant or even hazardous to use, however. Because ordinary horticulture grades of perlite contain dust that can irritate the lungs of workers, masks must be worn (figure 6.2.33B). Some brands contain a warning label noting that prolonged inhalation of crystalline silica can cause the delayed lung injury called silicosis and also that it can cause cancer in laboratory animals.

When shopping for a seed covering, the following characteristics need to be considered.

Texture. One of the primary functions of a seed covering is to maintain a "moist, but not wet" environment around the germinating seed. To the novice grower, it might seem logical to choose a material that holds water but this is not the case. A good seed mulch functions by creating a break in texture at the top of the growing medium (figure 6.2.33C). Because the growing medium is finer textured, water will not move into the coarser seed covering and so the surface of the medium remains moist, creating ideal conditions for seed germination.

Heat buildup. Germinating seeds are easily injured by heat. Temperatures at the surface of a dark growing medium or seed covering can significantly exceed that of the ambient growing environment. The intense sunlight in a greenhouse can quickly cause temperatures to reach damaging levels when dark seed mulches are used, so light-colored materials should always be used. Nurseries in coastal British Columbia used a dark grit for many years but switched to a very light gray material when many emerging seedlings were damaged during an unusually sunny spring.

Sterility. Because germinating seeds are very susceptible to fungal or bacterial attack, any material in direct contact with them obviously should be sterile. Some seed coverings are inherently sterile, including vermiculite and perlite, because they are heated to high temperatures during processing. *Sphagnum* peat moss is often considered to be sterile, but this has recently been shown to be false. Seed coverings need to be tested or sterilized with heat prior to use.

pH. Growers should try to maintain slightly acid (pH 5.0 to 6.0) conditions around germinating seeds to discourage damping-off fungi. Some seed coverings are made of crushed seashells, which are 90% calcium carbonate, and some coarse sands can also be calcareous. Such materials can cause the pH around the germinating seed to be too high, so growers should always test any potential new material. *Sphagnum* peat moss has the ideal pH and the large fibers can be milled to the proper size by forcing them through a 6.4-mm (0.25-in.) mesh screen (Emery 1988).

Weight. Seed coverings, such as grit or sand, are relatively heavy and can be costly to ship, so growers usually try to find a local supplier. Perlite is very lightweight, which can be a disadvantage because it tends to blow off the containers until they are irrigated, and can even be displaced by heavy water drops (Tinus and McDonald 1979).

6.2.9.2 Proper and uniform depth

The ideal depth of seed covering depends on the size of the seeds and, to some extent, on the type of irrigation system. A good general rule is to cover seeds to a depth that is approximately twice their smallest diameter (figure 6.2.33C) but this effect varies with seed size. In a study with Douglas-fir and western hemlock, the larger Douglas-fir seeds germinated and emerged at all the sowing depth treatments, whereas the small hemlock seeds had trouble at all but the shallowest depths (Minore 1985). Very small seeds or those requiring high light levels should be left uncovered and misted frequently or covered with a fine-textured material such as milled *Sphagnum* peat moss (Emery 1988). For example, Atlantic white-cedar seeds germinated best when pressed into the soil, left uncovered and then watered by a mist-

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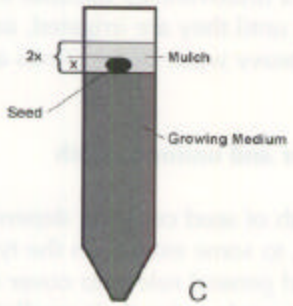
B



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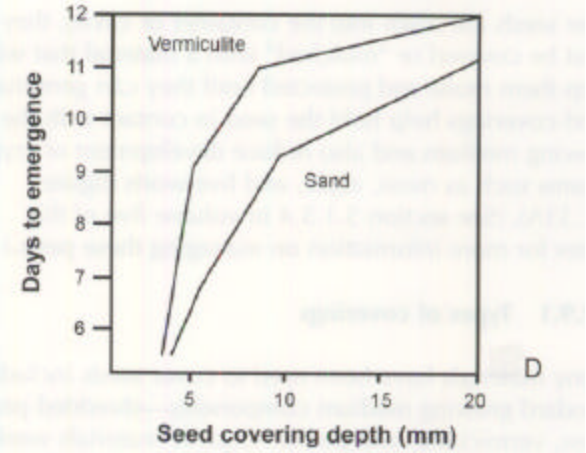

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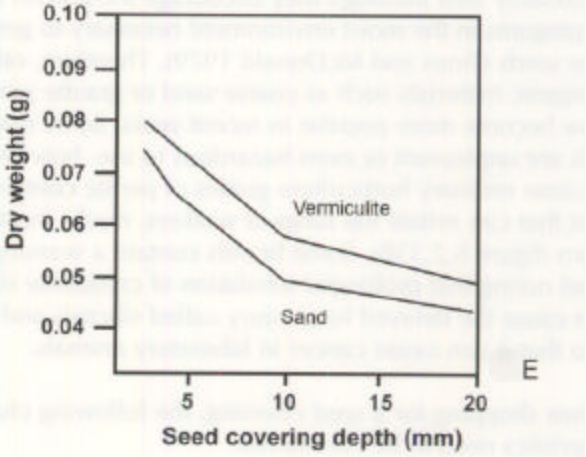

E

Figure 6.2.33—*After sowing, seeds and germinants are covered with a thin mulch to keep them moist and prevent growth of cryptogams* (**A**). *Light-colored materials are favored because they reflect intense sunlight but some, such as perlite, are dusty and require special precautions* (**B**). *The recommended depth of the seed covering is twice the seed width* (**C**). *If the covering is too deep it may inhibit germination* (**D**) *and even effect seedling size* (**E**). *An uneven seed covering is almost worse than none at all because seed germination rates will vary greatly. (D & E, modified from PFRA 1983.)*

ing system so that the growing medium surface remained damp (Boyle and Kuser 1994).

It is particularly difficult to maintain a uniform depth of seed mulch if containers are unevenly filled with growing medium. Any seed covering must be of uniform depth or seed germination and emergence will vary widely. Most seeds are phototropic and will germinate and emerge more quickly when they are not covered too deeply. The depth of the seed covering not only affects the rate of germination but also the size of the developing seedlings. The time for Siberian larch seedlings to emerge almost doubled as the seed covering increased from 5 to 10 mm (0.2 to 0.4 in.) and was different for vermiculite and sand (figure 6.2.33D). The size of the larch seedlings also decreased significantly as the depth of seed covering increased for both materials (figure 6.2.33E). In addition, seeds of low vigor may not have the energy to push through deep seed coverings.

6.2.10 Summary

The majority of forest and conservation species are propagated from seed to preserve the wide genetic adaptation that is critical to successful seedling establishment and growth in the natural environment. Growers must become familiar with the seed anatomy of the plants they wish to propagate and so a basic understanding of seed biology is mandatory. The seed source is important because it affects seedling growth in the nursery but, more importantly, seedlings must be adapted to the outplanting site. If the seed is not supplied by the customer, growers should insist on the proper seed source when purchasing seeds. High seed quality is essential to consistently produce crops of superior seedlings, and the only way to determine seed quality is by testing. Seed testing takes several weeks, so growers must allow enough time for testing before seeds are prepared for sowing. Unlike seeds of horticultural crops, which have been bred to germinate immediately after sowing, those of many forest and conservation species become dormant after they mature. Therefore, most need some sort of presowing treatment such as cold-moist stratification.

Seeds of most forest and conservation species are normally contaminated with fungi and bacteria and should be cleansed so that pathogens are not introduced into the nursery environment. The actual process of sowing seeds into containers varies with the type of seed and seed quality as determined by a viability test. Growers use three seed propagation methods (direct sowing, planting germinants, and transplanting emergents) and the choice depends on seed quality and dimensions. Direct sowing is most common and, although large or irregularly shaped seed must be sown by hand, the majority of commercial conifer seeds are mechanically sown. The number of seeds sown per container depends on seed quality and ranges from 1 to as many as 6. Seeds are covered with a mulch to protect the germinant and keep it moist. With multiple sowing, the extra seedlings must be physically thinned. Seed propagation will continue to be the most popular technique in forest and conservation nurseries and new innovations, such as miniplug transplants and precision sowing, will become more common.

6.2.11 References

6.2.11.1 Literature cited

AOSA [Association of Official Seed Analysts].] 995. Tetrazolium testing handbook (No. 29). Lincoln, NE: AOSA. 22 p.

Alexander NL, Flint HL, Hammer PA. 1984. Variation in cold-hardiness of *Fraxinus americana* stem tissue according to geographic origin. Ecology 65(4): 1087-1092.

Axelrood PE, Neumann M, Trotter D, Radley R, Shrimpton G, Dennis J. 1995. Seedborne Fusarium on Douglas-fir: pathogenicity and seed contamination. New Forests 9 (1): 35-51.

Balmer WE, Space JC. 1976. Probability tables for containerized seedlings. Atlanta: USDA Forest Service, Southern Area, State and Private Forestry. 27 p.

Banerjee M. 1994. A presowing treatment for spruce and lodgepole pine. Seed and Seedling Extension Topics 7(2): 7-8.

Barnett JP. 1971. Aerated water soaks stimulate germination of southern pine seeds. Res. Pap. SO-67. New Orleans: USDA Forest Service, Southern Forest Experiment Station. 9 p.

Barnett JP. 1972. Drying and storing stratified loblolly pine seeds reinduces dormancy. Tree Planters' Notes 23(3): 10-11.

Barnett JP. 1976. Sterilizing southern pine seeds with hydrogen peroxide. Tree Planters' Notes 27(3): 17-19.

Barnett JP. 1981. Imbibitional temperatures affect seed moisture uptake, germination, and seedling development. In: Proceedings,1 st Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SO-34. New Orleans: USDA Forest Service, Southern Forest Experiment Station: 41-45.

Barnett JP. 1985a. Estimating seed vigor by sugar exudates and radicle elongation. Tree Planters' Notes 36(31): 16-19.

Barnett, J.P. 1985b. Fluid drilling: a technique for improving nursery seedling establishment. In: Proceedings, 3rd Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SO-54. New Orleans: USDA Forest Service, Southern Forest Experiment Station: 38-41 .

Barnett JP. 1985c. Techniques for improving the performance of southern pine seeds in nurseries. In: Practices for the southern pines. Proceedings, International Symposium of Nursery Management, Montgomery, AL. Auburn University, AL: Alabama Agricultural Experiment Station: 102-112.

Barnett JP. 1986. Principles of sowing southern pine seeds. In: Schroeder, R.A., comp. Proceedings, Southern Forest Nursery Association Annual Meeting; 1986 July 22-24; Pensacola, FL. Tallahassee: Florida Division of Forestry: 22-31.

Barnett JP. 1997. Practical guidelines for producing longleaf pine seedlings in containers. Gen. Tech. Rep. SRS-14. Asheville, NC: USDA Forest Service, Southern Research Station. 28 p.

Barnett JP.; McGilvray JM. 1997. Practical guidelines for producing longleaf pine seedlings in containers. Gen. Tech. Rep. SRS-14. Asheville, NC: USDA Forest Service, Southern Research Station. 28 p.

Barnett JP, McLemore BF. 1967. Germination of loblolly pine seed hastened by soakings in aerated cold water. Tree Planters' Notes 18(2): 24-25.

Barnett JP, McLemore BF. 1984. Germination speed as a predictor of nursery seedling performance. Southern Journal of Applied Forestry 8: 157-162.

Barnett JP, Pesacreta TC. 1993. Handling longleaf pine seeds for optimal nursery performance. Southern Journal of Applied Forestry 17: 180-187.

Belcher EW, Leach GN, Gresham HH. 1984. Sizing slash pine seeds as a nursery practice. Tree Planters' Notes 35(2): 5-10.

Belcher EW, Waldrip BJ Jr. 1972. Effect of thiram on seed mold and germination of slash pine. In: Proceedings, Association of Official Seed Analysts No. 62. Corvallis: Oregon State University: 91-93.

Bergsten U. 1993. Removal of dead-filled seeds and invigoration of viable seeds: a review of a seed conditioning concept used on conifers in Sweden. In: Edwards DGW, ed. Dormancy and barriers to germination. Proceedings, IUFRO Project Group P2.04-00. Victoria, BC: Forestry Canada, Pacific Forestry Centre: 7-15.

Bir RE. 1992. Growing and propagating showy native woody plants. Chapel Hill: University of North Carolina Press. 192 p.

Bloomberg WJ. 1981. Disease caused by Fusarium in forest nurseries. In: Nelson PE, Toussan TA, Cook RJ. Fusarium: diseases, biology and taxonomy. University Park: Pennsylvania State University Press: 178-187.

Bonner FT. 1981. Measurement and management of tree seed moisture. Res. Pap. SO-177. New Orleans: USDA Forest Service, Southern Forest Experiment Station. 4 p.

Bonner FT. 1987. Effect of storage of loblolly and slash pine cones on seed quality. Southern Journal of Applied Forestry 11 : 59-65.

Bonner FT. 1990. Storage of seeds:potential and limitations for germplasm conservation. Forest Ecology and Management 35: 35-43.

Bonner FT. 1991. Seed management. In: Duryea ML, Dougherty PA, eds. Forest Regeneration Manual. Boston: Kluwer Academic Publishers: 51-73.

Bonner FA, tech. coord. [In press]. Woody plant seed manual, including tropical and range species. 3rd ed. Washington, DC: USDA Forest Service.

Bonner FT, Maisenhelder LC. 1974. Carya, hickory. In: Schopmeyer CS, tech. coord. 1974. Seeds of woody plants in the United States. Agric. Handbk. 450. Washington, DC: USDA Forest Service: 269-272.

Bonner FT, Vozzo JA. 1983. Measuring southern pine seed quality with a conductivity meter: does it work? In: Proceedings, Southern Nursery Conference. Savannah, GA. Tech. Bull. R8-TP4. Atlanta: USDA Forest Service, Southern Region, State and Private Forestry: 97-105.

Bonner FT, Vozzo JA. 1986. Evaluation of tree seed by electrical conductivity of their leachate. Journal of Seed Technology 10:142-150.

Bonner FT, Vozzo JA, Elam WW, Land SB Jr. 1994. Tree seed technology training course: instructor's manual. Gen. Tech. Rep. SO-106. USDA Forest Service, Southern Forest Experiment Station. 160 p.

Boyer JN, South DB, Muller C, Vanderveer H, Chapman W, Rayfield W. 1985. Speed of germination affects diameter at lifting of nursery-grown loblolly pine seedlings. Southern Journal of Applied Forestry 9: 243-247.

Boyle ED, Kuser JE. 1994. Atlantic white-cedar propagation by seed and cuttings in New Jersey. Tree Planters' Notes 45(3): 104-111 .

Buschena CA, Ocamb CM, O'Brien J. 1995. Biological control of fusarium diseases of conifer seedlings. In: Landis TD, Cregg B., tech. coords. National Proceedings, Forest and Conservation Nursery Associations. Gen. Tech. Rep. PNW-GTR-365. Portland, OR: USDA Forest Service, Pacific Northwest Research Station: 130-134.

Campbell RK, Sorensen FC. 1984. Genetic implication of nursery practices. In: Duryea ML, Landis TD, eds. Forest nursery manual: production of bareroot seedlings. Boston: Kluwer Academic Publishers: 183-191.

Campbell SJ, Landis TD. 1990. Managing seedborne diseaes in western forest nurseries. Tree Planters' Notes 41(4): 3-7.

Campbell TE. 1982. The effects of presoaking longleaf pine seeds in sterilants on direct seeding. Tree Planters' Notes 33(1): 8-11 .

Chaisurisri K, Edwards DGW, El-Kassaby, Y.A. 1994. Effects of seed size on seedling attributes in Sitka spruce. New Forests 8(1): 81-87.

Cullum FJ, Gordon AG. 1994. Dormancy release of tree and shrub seeds using a compost activator pretreatment. Combined Proceedings of the International Plant Propagators' Society 43: 125-130.

Czabator FJ. 1962. Germination value: an index combining speed and completeness of pine seed germination. Forest Science 8: 386-396.

Danielson J, Riley L. 1995. Western larch containerized seed orchards: adapting a concept to meet the production seed needs of the Pacific Northwest. In: Ecology and management of Larix forests: a look ahead. Proceedings of an international symposium. Gen. Tech. Rep. INT-319. Ogden, UT: USDA Forest Service, Intermountain Research Station: 478-481

Danielson RH, Tanaka Y. 1978. Drying and storing stratified ponderosa pine and Douglas-fir seeds. Forest Science 24:11-16.

Date L. 1994. Propagation of Pacific Northwest native plants from seed. Combined Proceedings of the International Plant Propagators' Society 43: 299-300.

Dirr MA, Heuser CW Jr. 1987. The reference manual of woody plant propagation: from seed to tissue culture. Athens, GA: Varsity Press. 239 p.

Deitschman GH, Jorgensen KR, Plummer AP. 1974. Purshia DC., bitterbrush. In: Schopmeyer CS, tech. coord. 1974. Seeds of woody plants in the United States. Agric. Handbk. 450. Washington, DC: USDA Forest Service: 686-691 .

Dumroese RK, Wenny DL. 1987. Sowing sized seed of western white pine in a containerized nursery. Western Journal of Applied Forestry 2(4): 128-130.

Dumroese RK, Wenny DL, Quick KE. 1990. Reducing pesticide use without reducing yield. Tree Planters' Notes 41(4): 28-32.

Dunlap JR, Barnett JP. 1982. Germination characteristics of southern pine as influenced by temperature. In: Proceedings, Southern Forest Tree Seedling Symposium. Gen. Tech. Rep. SO-37. New Orleans: USDA Forest Service, Southern Forest Experiment Station: 33-36.

Edwards DGW. 1981. Improving seed germination in *Abies.* In: Combined Proceedings of the International Plant Propagators' Society 31 : 69-78.

Edwards DGW. 1986. Special prechilling techniques for tree seeds. journal of Seed Technology 10: 151-171.

Edwards DGW. 1987. Methods and procedures for testing tree seeds in Canada. For. Tech. Rep. 36. Ottawa: Canadian Forestry Service. 32 p.

Edwards DGW. 1993. A historical overview of seed upgrading techniques and on to new roads of discovery. In: Proceedings, Joint Meeting of the B.C. Seed Dealers' Association and the Western Forest and Range Seed Council; 1993 June 2-4; Vernon, BC. Victoria, BC: Forestry Canada, BC Ministry of Forests: 21-24.

Edwards DGW, El-Kassaby YA. 1995. Douglas-fir genotypic response to seed stratification. Seed Science and Technology 23(3): 771-778.

Edwards DGW, Wang BSP. 1995. A training guide for laboratory analysis of forest tree seeds. Info. Rep. BC-X-356. Victoria, BC: Canadian Forest Service, Pacific Forestry Centre, 64 p.

El-Kassaby YA, Thomson AJ. 1996. Parental rank changes associated with seed biology and nursery practices in Douglas-fir. Forest Science 42(2): 228-235.

EI-Kassaby YA, Chaisurisri K, Edwards DGW, Taylor DW. 1993. Genetic control of germination parame ters of Douglas-fir, Sitka spruce, western redcedar, and yellow-cedar and its impact on container nursery production. In: Edwards DGW, ed. Dormancy and barriers to germination. Proceedings, IUFRO Project Group P2.04-00. Victoria, BC: Forestry Canada, Pacific Forestry Centre: 37-42.

El-Kassaby YA, Edwards DGW, Taylor DW. 1992. Genetic control of germination parameters in Douglas-fir and its importance for domestication. Silvae Genetica 41(1): 48-54.

Emery DE. 1988. Seed propagation of native California plants. Santa Barbara, CA: Santa Barbara Botanic Garden. 115.

Eremko RD, Edwards DGW, Wallinger D. 1989. A guide to collecting cones of British Columbia conifers. FRDA Rep. 055. Victoria: British Columbia Ministry of Forests and Forestry Canada. 114 p.

Finnerty TL, Hutton KM. 1993. Woody shrub propagation: a comprehensive approach. In: Landis TD, tech. coord. Proceedings, Western Forest Nursery Association; 1992 September 14-18; Fallen Leaf Lake, CA. Gen. Tech. Rep. RM-221. Fort Collins, CO: USDA Forest Service, Rocky Mountain Forest and Range Experiments Station: 82-91 .

Fleming RL, Lister SA. 1984. Stimulation of black spruce germination by osmotic priming: laboratory studies. Info. Rep. 0-X-362. Sault Ste Marie, ON: Canadian Forestry Service, Great Lakes Forest Research Center. 26 p.

Gelinas D. 1990. Seedling production in mini-cell containers in Quebec. In: Seedling production in Quebec: bareroot versus container seedlings. Proceedings, Northeastern State, Federal, and Provincial Nurseryman's Conference; 1990 July 23-26; Montreal, QC: Berthier, QC: Pepiniere Forestiere de Berthier.

Gordon AC. 1992. Seed manual for forest trees. Great Britain For. Comm. Bull. 83. London: Her Majesty's Stationery Office, Publications Centre. 132 p.

Gordon I, Hayes R. 1994. Control of woody root systems using copper compounds. Combined Proceedings of the International Plant Propagators' Society 44: 416-424.

Gosling PG. 1988. The effect of drying Quercus robur acorns to different moisture contents, followed by storage, either with or without imbibition. Forestry 62: 41-50.

Handreck KA, Black ND. 1994. Growing media for ornamental plants and turf. Randwick, NSW, Australia: University of New South Wales. 448 p.

Hartmann HT, Kester DE, Davies FT Jr, Geneve RL. 1997. Plant propagation: principles and practices. 6th ed. Englewood Cliffs, NJ: Prentice Hall. 770 p.

Hardin E. 1981. Quick test vs. standard germination test. In: Proceedings, Intermountain Nurseryman's and Western Forest Nursery Association Combined Meeting; 1980 August 12-14; Boise, ID. Gen. Tech. Rep. INT-109. Ogden, UT: USDA Forest Service, Intermountain Forest and Range Experiment Station: 71-73.

Haridi MB. 1985. Effect of osmotic priming with poly ethylene glycol on germination of Pinus elliottii seeds. Seed Science and Technology 13: 669-674.

ISTA [International Seed Testing Association]. 1985. International rules for seed testing. Seed Science and Technology 13(2): 299-355.

Jones L. 1962. Ninth annual report, Eastern Tree Seed Laboratory. Asheville, NC: USDA Forest Service, Southeastern Forest Experiment Station. 18 p.

Kolotelo D. 1996. Western redcedar seed. Seed and Seedling Extension Topics 9(1): 6-8.

Kolotelo D. 1997. Anatomy and morphology of conifer tree seed. For. Nursery Tech. Series 1.1. Victoria: British Columbia Ministry of Forests, Nursery and Seed Operations Branch. 60 p.

Kren LA. 1994. Seed for thought. Greenhouse Grower 12(11): 48-49.

Krugman SL, Jenkinson JL. 1974. Pinus L., pine. In: Schopmeyer CS, tech. coord. 1974. Seeds of woody plants in the United States. Agric. Handbk. 450. Washington, DC: USDA Forest Service: 598-638.

Krugman SL, Stein WI, Schmitt DM. 1974. Principles and general methods of producing and handling seeds. In: Schopmeyer CS, tech. coord. 1974. Seeds of woody plants in the United States. Agric. Handbk. 450. Washington, DC: USDA Forest Service: 5-52.

Landis TD, Simonich EJ. 1984. Producing native plants as container seedlings. In: Murphy PM, comp. The challenge of producing native plants for the Intermountain Area. Proceedings, Intermountain Nurserymen's Association 1983 Conference; 1983 August 8-11 ; Las Vegas, NV. Gen. Tech. Rep. I NT168. Ogden, UT: USDA Forest Service, Intermountain Forest and Range Experiment Station. 96 p.

Leadem C. 1996. A guide to the biology and use of forest tree seeds. Victoria, BC: Crown Publications. 20 p.

Littke WR. 1990. Seed fungi. In: Hamm PB, and others, eds. Growing healthy seedlings: identification and management of pests in Northwest forest nurseries. Spec. Pub. 19. Corvallis: Oregon State University, Forest Research Laboratory: 22-24.

Lowman BJ, Landis TD, Zensen F, Holland B. 1992. Bareroot nursery equipment catalog. MTDC Proj. Rep. 9224-2839. Missoula, MT: USDA Forest Service, Missoula Technology and Development Center. 204 p.

Macdonald B. 1986. Practical woody plant propagation for nursery growers. Volume 1. Portland, OR: Timber Press. 669 p.

May JT. 1985. Sowing and mulching. In: Southern pine nursery handbook. Atlanta: USDA Forest Service, Southern Region: 6-1 to 6-7.

McCreary D, Koukoura Z. 1990. The effects of collection date and pre-storage treatment on the germination of blue oak acorns. New Forests 3: 303-310.

McCure IG. 1995. The importance of selection and root pruning in container-grown seedling production of ornamental trees and shrubs. Combined Proceedings, International Plant Propagators' Society 44:121-122.

McLemore BF, Barnett JP. 1968. Moisture content influences dormancy of stored loblolly pine seed. Forest Science 14: 219-221 .

Minore D. 1985. Effects of sowing depth on emergence and growth of Douglas-fir, western hemlock, and noble fir seedlings. Canadian Journal of Forest Research 15: 935-940.

Moench RD. 1995. Rocky Mountain juniper production at the Colorado State Forest Service nursery. In: Landis TD, Cregg B, tech. coords. National Proceedings, Forest and Conservation Nursery Associations. Gen. Tech. Rep. PNW-GTR-365. Portland, OR: USDA Forest Service, Pacific Northwest Research Station: 52-53.

Moreno R. 1985. Do southern pine species benefit from cold stratification? In: South DB, ed. Proceedings, International Symposium on Nursery Management Practices for the Southern Pines; 1985 August 4-9; Montgomery, AL. Auburn University, AL: Auburn University, Department of Research Information: 113-117.

Muller C. 1993. Combination of dormancy-breaking and storage for tree seeds: new strategies for hardwood species. In: Edwards DGW, ed. Dormancy and barriers to germination. Proceedings, IUFRO Project Group P2.04-00. Victoria, BC: Forestry Canada, Pacific Forestry Centre: 79-85.

Muller C, Bonnet-Masimbert M. 1989. Storage of non dormant hardwood seeds: new trends. Annales des Sciences Forestieres 46(Suppl): 92s-94s.

Neumann M, Trotter D, Kolotelo D. 1997. Seed sanitation method to reduce seedborne Fusarium levels on conifer seed. Seed and Seedling Extension Topics 100/2): 1-35.

Olson DF Jr, Gabriel WJ. 1974. Acer L., maple. In: Schopmeyer CS, tech. coord. Seeds of woody plants in the United States. Agric. Handbk. 450. Washington, DC: USDA Forest Service: 187-194.

PFRA. 1983. Prairie Farm Rehabilitation Act (PFRA) Annual Report. Indian Head, SK: PFRA Tree Nursery: 17.

Pawuk WH. 1978. Damping-off of container-grown longleaf pine seedlings by seedborne Fusaria. Plant Disease Reporter 62: 82-84.

Piotto B. 1994. Sowing of pelletized seed: a technique to simplify Eucalypt raising in tropical nurseries. Tree Planters' Notes 45(2):58-62.

Read RA. 1983. Ten-year performance of ponderosa pine provenances in the Great Plains of North America. Res. Pap. RM-250. Ft. Collins, CO: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station. 17 p.

Roche S, Dixon KW, Pate JS. 1997. Seed ageing and smoke: partner cues in the amelioration of seed dormancy in selected Australian native species. Australian Journal of Botany 45: 783-815.

Rudolf PO. 1974. Tree-seed marketing controls. In: Schopmeyer CS, tech. coord. Seeds of woody plants in the United States. Agric. Handbk. 450. Washington, DC: USDA Forest Service: 153-166.

Rudolf PO, Dorman KW, Hitt RG, Plummer AP. 1974. Production of genetically improved seed. In: Schopmeyer CS, tech. coord. Seeds of woody plants in the United States. Agric. Handbk. 450. Washington, DC: USDA Forest Service: 53-74.

Scarratt JB. 1991. Effect of early transplanting upon growth and development of spruce and pine seedlings in paperpot containers. New Forests 4(4): 247--259.

Schoprneyer CS, tech. coord. 1974. Seeds of woody planes in the United States. Agric. Handbk. 450. Washington, DC: USDA Forest Service. 883 p.

Schwartz M. 1993. Germination math: calculating the number of seeds necessary per cavity for a given number of live seedlings. Tree Planters' Notes 44(1 09-20.

Simak M. 1984. A method for removal of filled dead seeds from a sample of Pinus *contorta.* Seed Science and Technology 12:767-775.

Simak M. 1976. Germination improvement of Scots pine seeds from circumpolar regions using polyethylene glycol. In: Proceedings, Second International Symposium on Physiology of Seed Germination; IUFRO Working Group 52.01.06; Fuji, Japan: 145--153.

Singh O, Sharma HP, Sharma SK. 1984. Effect of root clipping on the growth of transplanted spruce seedlings. Journal of Tree Science 3(1/2): 149-152.

Singh DP, Hooda MS, Bonner FT. 1991. An evaluation of scarification methods for seeds of two leguminous trees. New Forests 5: 139-145.

South DB, Young C. 1994. Germinant sowing in South Africa. Combined Proceedings of the International Plant Propagators' Society 44: 266-270.

Stein V\1I. 1965. Afield test of Douglas-fir, ponderosa pine, and sugar pine seeds treated with hydrogen peroxide. Tree Planters' Notes 71 : 25-29.

Stein V\'I, Danielson R, Shaw N, Wolff S, Gerdes D. 1986. Users guide for seeds of western trees and shrubs. Gen. Tech. Rep. PNW-193. Corvallis, OR: USDA Forest Service, Pacific Northwest Research Station. 45 p.

Suresh KK, Swaminathan C, Vinaya Rai RS. 1994. Increasing nursery efficiency by use of presprouted seeds in *Hardwickia binata* Roxb. Indian Journal of Forestry 17(4): 356-358.

Sutherland JR, Van Eerden E. 1980. Diseases and insect pests in British Columbia forest nurseries. Joint Rep. 12. Victoria, BC: British Columbia Ministry of Forests and Canadian Forestry Service, Pacific Forest Research Centre. 55 p.

Tanaka Y, Kleyn NJ, Harper LM. 1986. Seed stratification of Engelmann spruce and lodgepole pine: the effect of stratification duration and timing of surfacedrying. Forestry Chronicle 62: 147-151 .

Taylor AG, Harman GE. 1990. Concepts and technologies of selected seed treatments. Annual Review Phytopathology 28: 321-339.

Tinus RW, McDonald SE. 1979. How to grow tree seedlings in containers in greenhouses. Gen. Tech. Rep. RM-60. Ft. Collins, CO: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station. 256 p.

Trindle JDC. 1995. Personal communication. Corvallis, OR: USDA Natural Resources Conservation Service, Plant Materials Center.

Trindle JDC. 1996. Evaluating acid scarification effects on dormant *Arctostaphylos nevadensis seeds.* International Plant Propagators' Society Combined Proceedings (1995) 45: 312-314.

USDA Agricultural Research Service. 1981. Collecting, processing, and germinating seeds of western wildland plants. Rep. ARM-W-3. Oakland, CA: USDA Agricultural Research Service. 44 p.

USDA Forest Service. 1948. Woody-plant seed manual. Misc. Publ. 654. Washington, DC: USDA Forest Service. 416 p.

USDA Forest Service. 1995. Commercial suppliers of tree and shrub seed in the United States. Misc. Rep. R8-MR 33. Atlanta: USDA Forest Service, Southern Region. 97 p.

Vankus V. 1997. The tetrazolium estimated viability test for seeds of native plants: In: Landis TD, Thompson JR, tech. coords. National Proceedings, Forest and Conservation Nursery Associations. Gen. Tech. Rep. PNW-GTR-419. Portland, OR: USDA Forest Service, Pacific Northwest Research Station: 57-62.

Weber FR, Stoney C. 1986. Reforestation in arid lands. Arlington, VA: Volunteers in Technical Assistance. 335 p.

Wells 00, Wakeley PC. 1966. Geographic variation in survival, growth, and Fusiform rust infection of planted loblolly pine. Forest Science Monograph 11: 1-40.
Wenny DL, Dumroese RK. 1987. Germination of conifer seeds surface-sterilized with bleach. Tree Planters' Notes 38(3): 18-21.
Williams RD, Hanks SH. 1994. Hardwood nursery guide. Agric. Handbk. 473. Washington, DC: USDA Forest Service. 78 p.
Wood B. 1994. Conifer seedling grower guide. Smoky Lake, AB: Pine Ridge Forest Nursery 73 p.

6.2.11.2 General seed propagation references

AOSA [Association of Official Seed Analysts]. 1985. Handbook on seeds of browse shrubs and forbs. Tech. Pub. R8-TP8. Atlanta: USDA Forest Service, Southern Region. 246 p.
Bonner FA, tech. coord. [In press]. Woody plant seed manual, including tropical and range species. 3rd ed. Washington, DC: USDA Forest Service.
Bonner FT, Vozzo JA, Elam WW, Land SB Jr. 1994. Tree seed technology training course: instructor's manual. Gen. Tech. Rep. SO-106. USDA Forest Service, Southern Forest Experiment Station. 160 p.
Dirr MA, Heuser CW Jr. 1987. The reference manual of woody plant propagation: from seed to tissue culture. Athens, GA: Varsity Press. 239 p.
Emery DE. 1988. Seed propagation of native California plants. Santa Barbara, CA: Santa Barbara Botanic Garden. 115.
Hartmann HT, Flocker WJ, Kofranek AM. 1981. Plant science: growth, development, and utilization of cultivated plants. Englewood Cliffs, NJ: Prentice-Hall. 676 p.
Kolotelo D. 1997. Anatomy and morphology of conifer tree seed. For. Nursery Tech. Series 1.1. Victoria: British Columbia Ministry of Forests, Nursery and Seed Operations Branch. 60 p.
Landis TD, Simonich EJ. 1984. Producing native plants as container seedlings. In: Murphy PM, comp. The challenge of producing native plants for the Intermountain Area. Proceedings, Intermountain Nurserymen's Association 1983 Conference; 1983 August 8-11; Las Vegas, NV. Gen. Tech. Rep. INT168. Ogden, UT: USDA Forest Service, Intermountain Forest and Range Experiment Station. 96 p.
Leadem C. 1996. A guide to the biology and use of forest tree seeds. Victoria, BC: Crown Publications. 20 p.
Owen JN, Blake MD. 1985. Forest tree seed production: a review of the literature and recommendations for future research. Info. Rep. PI-X-53. Chalk River, ON: Canadian Forestry Service, Petawawa National Forestry Institute. 161 p.
Schopmeyer CS, tech. coord. 1974. Seeds of woody plants in the United States. Agric. Handbk. 450. Washington, DC: USDA Forest Service. 883 p.
USDA Forest Service. 1948. Woody-plant seed manual. Misc. Publ. 654. Washington, DC: UDA Forest Service. 416 p.
Vories KC. 1981. Growing Colorado plants from seed: a state of the art. Volume 1, Shrubs. Gen. Tech. Rep. INT-103. Ogden, UT: USDA Forest Service, Intermountain Forest and Range Experiment Station. 80 p.
Wasser CH. 1982. Ecology and culture of selected species useful in revegetating disturbed lands in the West. Pub. FWS/OBS 82/56. Washington, DC: USDI Fish and Wildlife Service. 347 p.
Wright RCM, Titchmarsh A. 1981. The complete book of plant propagation. London: Ward Lock Ltd. 180 p.
Young JA, Young CG. 1992. Seeds of woody plants in North America. Portland, OR: Dioscorides Press. 407 p.